Evaluation of Dry-Land Ergometry in Assessment of Cardiopulmonary and Metabolic Responses to Arm and Leg Exercise in Swimmers

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Abstract

Dry-land ergometry has been proposed as an alternative method to water-based testing in an attempt to circumvent the difficulties associated with physiological assessment of swimmers during swimming itself. The aim of the studies presented in this thesis was to evaluate the usefulness of dry-land ergometry. The objectives of the studies presented in this thesis were to ascertain whether dry-land measurements could differentiate between trained and untrained swimmers, assess the effects of training and reflect water-based measurements. To realise this aim and the objectives, three studies that assessed physiological parameters of swimmers using dry-land ergometry and water-based testing were undertaken.

The first study compared lactate and oxygen uptake responses to separate dry-land arm-pulling and leg-kicking in recreational (RSW) and collegiate swimmers (SW). The exercise intensity at a blood lactate concentration of 4 mmol·l^{-1} (EI_{4mM}) and the peak oxygen uptake ($\dot{V}O_{2peak}$), peak exercise intensity (EI_{peak}) and peak lactate (HLa_{peak}) responses to incremental arm-pulling and leg-kicking were established for both groups. The results showed that, for arm-pulling, SW achieved higher EI_{4mM} (94 ± 6.0 W versus 70 ± 6.3 W; $P<0.05$) and EI_{peak} (114 ± 6.0 W versus 90 ± 4.0 W; $P<0.05$) than RSW, whereas, for leg-kicking, none of the responses differed between the two groups. These results suggested that arm conditioning was enhanced in SW and this was reflected in the dry-land measurements of EI_{4mM} and EI_{peak}. Therefore, it was possible to establish the differences in physiological responses between SW and RSW using dry-land ergometry.

The second study assessed the effects of arms- versus legs-only swimming training on performance indices and gas exchange responses to separate dry-land arm-pulling and leg-kicking in competitive swimmers. Two groups of swimmers performed arms- (ARMS) or legs-only (LEGS) swimming exercises for 20% of their training time, 3 times a week for six weeks. Water-based (swim trials) and dry-land assessments were conducted prior to and immediately after the 6-week training period. The swim trials included a 200 m arms-only (200_{ARMS}), a 200 m legs-only (200_{LEGS}) and a 400 m (400_{FULL}) front crawl test. Distance per pull (DPP) and distance per kick (DPK) for 200_{ARMS} and 200_{LEGS} were calculated from video recordings. The dry-land assessments included measurements of oxygen uptake ($\dot{V}O_2$), ventilatory threshold (VT) and total exercise time (TET) during an incremental arm-pulling and leg-kicking exercise test. The results showed that arm training improved 200_{ARMS} (184 ± 10.0 s versus 164 ± 6.0 s) and DPP (+10 ± 3%) in the ARMS and leg training improved 200_{LEGS} (223 ± 10.0 versus 211 ± 10.0 s) and DPK (+5 ± 2%) in the LEGS (all at $P<0.05$). The changes due to arm training were reflected in the arm-

pulling measurements of increased VT_W (+20 ± 3%), reduced $\dot{V}O_2$ at 60W (-18 ± 2%) and increased TET (465 ± 8 s versus 675 ± 15 s), whereas the changes due to leg training were reflected in VT_W (+37 ± 5%) and reduced $\dot{V}O_2$ at 60W (-20 ± 3%). These results suggested that arms- or legs-only swimming training induces changes in arms- or legs-only swimming performance, but these do not necessarily translate into improved full-stroke swimming performance. Also, results indicate that dry-land ergometry can detect the changes due to arms- or legs-only swimming training in the physiological responses to arm-pulling or leg-kicking.

The third study compared the cardiopulmonary responses to whole-body, arms- and legs-only dry-land exercise and free swimming. The peak oxygen uptake ($\dot{V}O_{2peak}$) and peak heart rate (HR_{peak}) responses to whole-body, arm-pulling and leg-kicking exercise were established in both exercise modalities. The results showed that $\dot{V}O_{2peak}$ was higher in whole-body exercise than arms-only or legs-only exercise in both exercise modalities (dry-land: 3.69 ± 0.18 $l \cdot min^{-1}$ versus 3.18 ± 0.43 $l \cdot min^{-1}$ and 3.15 ± 0.54 $l \cdot min^{-1}$, respectively; $P<0.05$, swimming: 4.12 ± 0.84 $l \cdot min^{-1}$ versus 3.36 ± 0.52 $l \cdot min^{-1}$ and 3.55 ± 0.43 $l \cdot min^{-1}$, respectively; $P<0.05$) and also that whole-body $\dot{V}O_{2peak}$ was 10% higher during free swimming than during dry-land exercise. No differences were noted for HR_{peak} between whole-body, arms-only and legs-only exercise in both exercise modalities. These results suggested that the higher $\dot{V}O_{2peak}$ noted for whole-body free swimming compared to combined arm-leg exercise could be due to limitations in the design of the dry-land ergometer used as the difference was small. Therefore, it was shown that dry-land measurements compare favourably with water-based measurements.

The use of dry-land ergometry presents several limitations, which are mainly concerned with the design of this equipment. However, all the above findings demonstrate that dry-land ergometry might be a valuable tool for assessment of those physiological responses (i.e. continuous measurement of gas exchange measures) that, at present, are difficult to be conducted in the water. Therefore, dry-land ergometry might be used as an alternative and/or supplement to water-based testing.

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$\dot{V}O_2$	Oxygen uptake per unit time
$\dot{V}O_{2peak}$	Peak oxygen uptake per unit time
$\dot{V}O_2$-60	Oxygen uptake per unit time at 60 W
EI_{peak}	Peak exercise intensity
EI_{4mM}	Exercise intensity at a blood lactate concentration of 4 mM
VT	Ventilatory threshold
HR_{peak}	Peak heart rate
$\dot{V}O_2$/HR	The relationship between oxygen uptake and heart rate

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To my father,

who taught me right from wrong
and made me believe in myself.

CHAPTER 1

INTRODUCTION AND REVIEW OF LITERATURE

1.1. Historical overview of exercise testing

The use of exercise in investigating physiological function can be dated back to the first modern Olympics in 1896, when the athletic feats were observed and specific training programmes were devised to foster improvements in either muscle hypertrophy and strength or endurance (Robergs and Roberts, 1997). Such observations formed an advanced field of enquiry, which eventually led to the development of a new science called 'Physiology of Exercise' or according to others 'Exercise Physiology'. Originally, the purpose of all investigations in this field was to identify ways to develop overall fitness, prescribe training exercises for fitness and sport and clarify matters relating to personal health and hygiene (McArdle et al., 1996).

During the first three decades of the 20th century a large part of research was devoted to the study of the body's responses to exercise (Robergs and Roberts, 1997) and outstanding contributions were made to the science exercise physiology. For example, the study of oxygen consumption during exercise (Hill and Lupton, 1923) and the development of indirect calorimetry (Lusk, 1928) set the basis for the establishment of fundamental concepts, such as maximal oxygen uptake ($\dot{V}O_{2max}$) and energy expenditure. The formation of the Harvard Fatigue Laboratory by L.J. Henderson in 1927 (Robergs and Roberts, 1997) promoted the scientific study of the effects of exercise on the human body. The research produced in this laboratory had tremendous impact upon the study of metabolism during exercise and the effects of ageing on human performance (Buskirk, 1992).

For the past thirty years at least, there has been increased effort to optimise performance in the different sports. Participation has evolved from a frivolous activity to a profitable profession. As a result, the objective of research in physiology of exercise has, in some instances, been to identify formulae for success through exercise testing. Assessments of physiological responses to exercise in the 'field'

have presented several limitations, which have mainly been associated with the continuous movement of the athlete. The need for assessment and close monitoring of athletic performance in a controlled environment led to the development of laboratory-based equipment, such as exercise ergometers (*ergo* = work, *meter* = measurement; Bowers and Fox, 1984) that can be used to replicate the sporting activity whilst manipulating exercise intensity.

The most commonly used ergometers in a sporting context are the cycle ergometer and the treadmill (running ergometer). Due to the 'specificity of training' principle (Strømme et al., 1977), this type of equipment should only be used to assess physiological responses to exercise in athletes whose sporting activity involves cycling or running. In swimming, the difficulty of conducting physiological assessments in the water led to the development of different types of ergometers. Initially, the focus of research was upon developing water-based ergometers, such as the swimming flume and the tethered swimming and the measurement of active drag (MAD) devices. Recently, there has been an increased interest in using laboratory-based ergometry to assess physiological measures of swimmers. One example of laboratory-based ergometry is the swim bench, which was initially developed to be used in strength training of swimmers.

One main advantage of laboratory-based ergometry is associated with the ability to regulate and quantify exercise intensity externally. When controlling exercise intensity, metabolic responses can be compared between different individuals and at various levels of physiological function (Robergs and Roberts, 1997). In swimming, improvements in swimming performance offer little explanation of the underpinning adaptations in physiological mechanisms. Laboratory-based ergometry, such as the swim bench offers the attractive opportunity of relating physiological measures to exercise intensity. This opportunity may not directly explain swimming performance, but may be used to monitor the improvements in the power output of the upper body of swimmers. It has been shown previously that improvements in swimming

performance are associated with increased arm power output of swimmers as measured using swim bench exercise (Charbonnier et al., 1975; Toussaint and Vervoorn, 1990).

1.2. Research in physiology of swimming

Research in the physiology of swimming has a history that originates in the first decade of this century (Lewillie, 1983), yet the understanding of physiological responses to swimming has lagged behind that of other sports, such as cycling or running. This has been due, largely, to difficulties in assessing physiological measures during swimming itself. In particular, these difficulties have hindered the continuous measurement of physiological variables, such as oxygen uptake, blood lactate and power output during swimming. Despite the limitations, a considerable body of knowledge about swimming physiology has been made available to swimmers and coaches. This has resulted from theoretical ingenuity, such as the estimation of oxygen uptake using a technique called 'backward extrapolation', where post-exercise oxygen uptake is measured in recovery immediately after maximal swimming (Costill et al., 1985). Practical ingenuities have mainly included the design of appropriate ergometry to circumvent the problems arising from physiological assessment in the swimming pool. One example of such ergometry is the swimming flume, which has been designed to provide an alternative testing environment for physiological assessments, whilst simulating the conditions of a swimming pool. Other ergometry, such as the swim bench, has been primarily designed for training purposes, but has equally been used in physiological assessment of swimmers (Reilly, 1990).

1.3. Historical overview of general swimming assessment methods

1.3.1. Water-based methods

There has been a plethora of methods that have been used to assess swimmers. The earliest methods focused upon assessments carried out in the water. Such assessments

were first initiated in the late 19th century, when swimming was established as a sport by inclusion in the first Olympic Games of 1896. The need for swimming assessments arose from increased competition in these Games and also in long distance swimming events, such as swimming the English Channel (Lewillie, 1983). Research interest was drawn towards assessing swimming performance in the water to identify success in swimming events. This historical development has been reviewed and presented elsewhere in detail (Lewillie, 1983).

The first reported water-based assessment method used towing of an active swimmer behind a boat and measured the forces generated during swimming using a dynamometer (Dubois-Reymond, 1905). In later studies, active towing was used to measure water resistance during swimming. These studies employed the use of different equipment, such as a resistograph (Karpovich, 1933), a modified resistograph (Alley, 1952; Councilman, 1955) and a ship model basin (Clarys et al., 1974).

Another water-based assessment method included the measurement of speed fluctuations during swimming. This involved the use of a system of cables and pulleys (Miyashita, 1971). The forces generated during swimming have also been assessed. This method used a system of weights arranged vertically on a stationary platform (tethered swimming; Magel et al., 1974) or a platform moving at constant speed alongside the swimmer in a circular pool (Di Prampero et al., 1974). Furthermore, the deviation between extreme velocities during swimming has been assessed using a linear accelerometer (Holmér, 1979).

In the 1980s, a group of Dutch researchers developed a water-based system to enable measurement of active drag to be achieved during free swimming (MAD system; Hollander et al., 1986). The design of this system demonstrated the main elements of tethered swimming, but the main difference was that the swimmer was free to propel his body forward using the front crawl swimming action. It was possible to perform

measurements of active drag during the arm-pulling action of the front crawl stroke using this system.

A 'key' development in swimming research was the construction of an aquatic 'swim mill'. This consisted of a water tank, through which water was propelled using a pump. In this tank water velocity could be manipulated, thereby allowing performance to be assessed against constant or increasing water velocities (Åstrand and Englesson, 1971). This equipment was later modified to form a 'swimming flume', which was used to study physiological responses to swimming (Holmér, 1972; Holmér and Haglund, 1978) and also, water resistance in relation to body size (Miyashita and Tsunoda, 1978).

1.3.2. Dry-land methods

In addition to water-based assessment methods, there have been methods which have used determinations in the laboratory. Swimmers have been assessed in the laboratory using arm-cranking and cycling and also ergometry which attempts to replicate the front crawl swimming action (swim bench). The swim bench was developed in the late 1970s to be used in dry-land strength training of swimmers (Flavel and Councilman, 1980). It comprises a dry-land exerciser that was specially designed to fulfil swimming specifications, such as accommodating resistance and to replicate the arm stroke characteristics of swimming (Councilman, 1980). Later, the swim bench was also used in physiological assessment of swimmers (Sharp et al., 1982; Clarys, 1985). This was due to its ability to circumvent the difficulties arising from water-based testing. One of the difficulties associated with measurements of oxygen uptake during swimming is related to the use of gas collection apparatus. This involves the use of a mouthpiece with headgear, which may increase drag, thereby retarding swimming motion. In addition, the mouthpiece itself has been known to offer resistance to breathing (Bayly et al., 1987). More importantly, this arrangement poses a safety risk, as apart from the inconvenience it causes to the swimmer, there is possibility of water inhalation. Indeed, it was shown that it is possible to measure

oxygen uptake of swimmers at increasing intensities of exercise using the swim bench (Swaine and Reilly, 1983). Moreover, the opportunity to quantify exercise intensity as power output has provided opportunities for novel assessment methods for swimmers. This has not been possible previously through use of any other type of swimming ergometry.

1.4. The most commonly used swimming assessment methods

A detailed description of the four most commonly used swimming assessment methods is given in the following section, with particular focus upon the respective ergometers. Swimming assessment methods can be classified into two main categories: a) *water-based methods* that use tethered swimming, measurement of active drag and flume swimming and b) *dry-land methods* that use swim bench exercise.

1.4.1. Tethered Swimming

Tethered swimming is the form of swimming exercise where the subject remains stationary whilst attached or 'tethered' to a cable and pulley system by means of a belt worn around the waist (Diagram 1; Magel et al., 1974). The amount of weight attached to the cable can be increased periodically, thereby forcing the swimmer to exert more effort to maintain his/her position, whereas the force exerted by the swimmer must be sufficient to maintain the pulley at a given height. Alterations in the original design of the stationary platform in tethered swimming led to the development of a moving platform. This system is called 'semi-tethered' swimming (Diagram 2; Di Prampero et al., 1974), as the swimmer is no longer stationary. In this system the pulleys are attached to the platform, which in turn connects with the subject. The platform can be positioned either in front of the swimmer moving at constant speed or behind the swimmer being pulled along the pool side by the swimmer. Further improvements in the use of tethered swimming led to the development of a 'swimming power output system' (Costill et al., 1986). When using

this system the swimmer is tethered to a cable, which is connected to a computer. By use of specialised software, the forces that the swimmer generates while swimming can be converted to power output. A diagramatic representation of the 'swimming power system' can be found in Robergs and Roberts (1997). Tethered swimming is a useful method as it can be used to measure the forces generated during swimming and also to assess propulsive power.

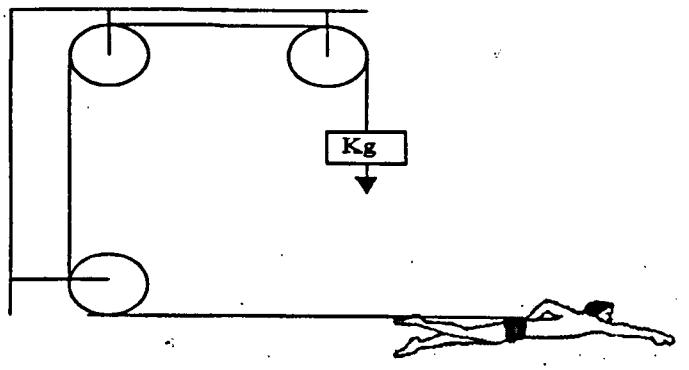

Diagram 1. Tethered swimming showing the system of cables and pulleys and the way the swimmer is 'tethered' to the system. Redrawn from McArdle et al. (1991), *Exercise Physiology: Energy, Nutrition and Human Performance*, p. 191.

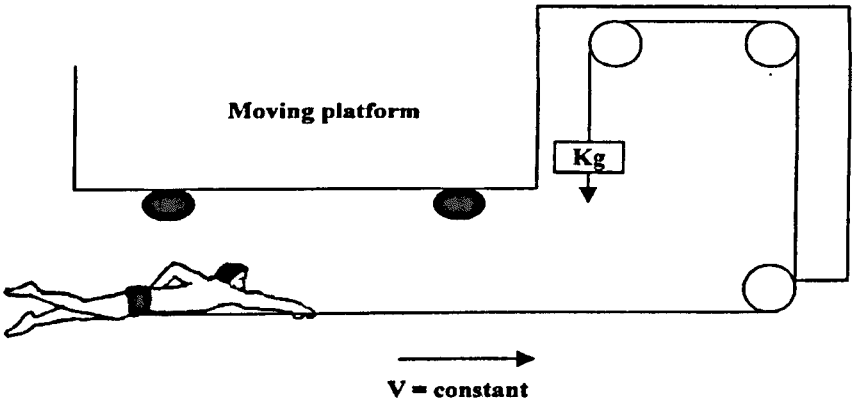

Diagram 2. Semi-tethered swimming showing the platform moving at constant velocity alongside the swimmer and the different arrangement of the system of cables and pulleys. Redrawn from DiPrampero et al. (1974), Energetics of swimming in man, *Journal of Applied Physiology*, 237: 1.

Although tethered swimming is a useful tool in assessment of swimmers in the water, its use presents limitations that are mostly associated with the stationary position of the swimmer in the water. It has been suggested that during tethered swimming the movements of the arms and the legs through the water differ from free swimming. Also, swimming speed and drag are minimal (Lewillie, 1971; Hoecke and Gruendler, 1975). It has also been postulated that the swimmers' technique during tethered swimming is not at all similar to that used in free swimming (Wilmore and Costill, 1994). Furthermore, tethered swimming measurements can only provide information on propulsive forces generated by the whole-body (Di Prampero et al., 1974) of the swimmer. In addition, it is difficult to use tethered swimming to assess the separate responses to arm or leg exercise at the same given swimming speed.

1.4.2. The MAD system

The MAD system has a similar structure to that of tethered swimming. This system was especially designed to measure active drag during front crawl swimming (Hollander et al., 1986). It comprises a system of fixed push-off pads mounted 1.35 m apart on two 23-metre horizontal rods, which are placed 1.25 m parallel to each other. This arrangement enables the swimmer to swim in both directions using the system (Toussaint et al., 1988). The rods are tied at each pool end and are fixed at 0.8 m below the water surface. At the end of the pool, one of the rods is connected to a force transducer linked to an on-line computer using a 12-bit analogue-to-digital converter that operates at a frequency of 100 Hz. This enabled the propelling force that the swimmer generates during the push-off action to be measured at each pad. Whilst swimming front crawl, the swimmer places alternate hands on the pads and performs the swimming action, thereby pushing on the pads and moving forward. It has been suggested that, at a constant velocity of swimming, the average propulsive force will be equal to the average drag force (Reilly et al., 1990).

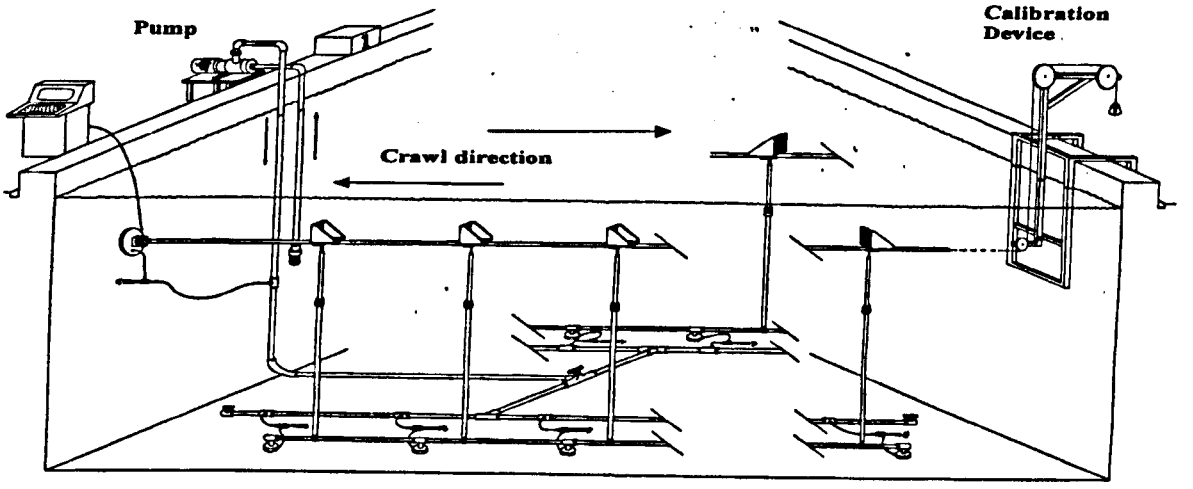

Diagram 3. The MAD system showing the system of fixed push-off pads, the horizontal rods and the way these are fixed onto the pool end and under the water surface. Reproduced by permission from Toussaint et al. (1988), 'Measurement of efficiency in swimming man' in *Swimming Science V*, edited by B.E. Ungerechts, K. Wilke and K. Reischle (Champaign, IL: Human Kinetics), p. 47.

The MAD system is a useful innovation as it provides an alternative method for measuring propulsive power during front crawl swimming (Toussaint et al., 1988; Toussaint et al., 1990), but its use has certain disadvantages. One of these disadvantages is associated with possible alterations in swimming technique, which are made so that the arm-stroking pattern coincides with the fixed position of the push-off pads. Another disadvantage is that the current arrangement of the MAD system allows only measurement of active drag of the arm-pulling and not the leg-kicking front crawl action. The amount of active drag generated by leg-kicking has been indirectly estimated by measuring whole-body and arms-only active drag and subtracting the latter from the former (Hollander et al., 1986). These findings suggested that active drag during leg-kicking accounts for approximately 11% of whole-body propulsion. However, the active drag of the leg-kicking action during

front crawl swimming was not measured directly and therefore, these findings must be viewed with caution. The contribution that the leg-kicking component of front crawl swimming makes to the overall physiology of swimming must be further investigated before definitive conclusions can be made.

1.4.3. The Swimming Flume

The swimming flume allows swimmers to simulate closely their 'pool' swimming strokes. Otherwise termed the swimming treadmill (Diagram 4; Åstrand and Englesson, 1971), it consists of a tank where water can be circulated at varying set flow rates. Sometimes, it is surrounded by an environmental chamber, which controls atmospheric pressure and other environmental conditions during swimming. It operates by propeller pumps that circulate water past the swimmer, who attempts to maintain body position in the flume. The pump circulation can be increased or decreased to vary the speed at which the swimmer must swim (Wilmore and Costill, 1994). The swimming treadmill has been used to assess physiological measures and biomedical aspects during swimming as it is possible to simulate actual performance conditions when using this equipment (McArdle et al., 1996).

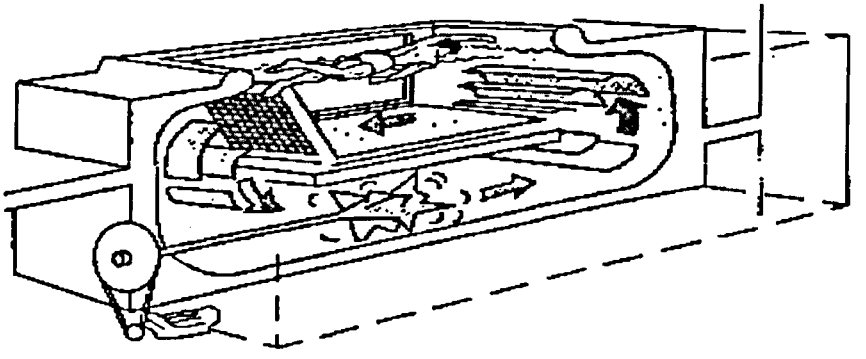

Diagram 4. The swimming flume showing the tank, the propeller pump and the anti-clockwise flow of water. Permission to reproduce this diagram has been sought from Åstrand P.O. and Englesson S. (1971): A swimming flume. *Journal of Applied Physiology*, 33: 514.

The swimming flume is considered to be the most successful technical innovation in the swimming world, as it provides the ideal environment for physiological measurements of swimmers during swimming (Wilmore and Costill, 1994). However, this sophisticated assessment system can only assess physiological measures in relation to swimming speed (Klauck and Ungerechts, 1997). It is not possible to measure propulsive power, or indeed, any kind of power output measure from the exercising limbs of the swimmer. The swimming flume is an elaborate method of testing physiological characteristics of swimmers during swimming. The main advantage of this method is that the test environment is identical to the swimmer's training environment. Another advantage is that it allows standardisation of procedures, especially of those referring to swimming speed, which results in increased accuracy and reproducibility of measurements (Holmér, 1972). Swimming speed can be easily manipulated either to remain constant throughout a set distance or to increase gradually. This allows determination of physiological measures such as maximum oxygen uptake (Bonen et al., 1980).

The main disadvantage of using the swimming flume is the high cost of installation and maintenance of this equipment. Contrary to its equivalent for runners (treadmill), the swimming flume requires spacious facilities for its installation and specialised personnel for its operation and maintenance. In most cases, research institutions are unable to utilise the required space or finances to maintain such expensive equipment within their facilities. Other disadvantages include the quantity of energy lost in turbulence (Holmér, 1974) and the fact, that the amount of work performed is measured only in the direction of progression (Holmér and Haglund, 1978). Also, in water-based assessments using the swimming flume, it is not possible to elucidate the contribution that leg-kicking makes to the overall physiological responses to swimming whilst the arms and the legs are exercised simultaneously.

1.4.4. The Swim Bench

The swim bench is a dry-land ergometer which was initially developed as a training device to be used in strength training of swimmers (Thornton and Flavel, 1977), but later was also used in physiological assessment of swimmers (Armstrong and Davies, 1981; Swaine and Reilly, 1983; Swaine and Zanker, 1996). In the late 1970s, the swim bench incorporated the structure of an early swimming machine which was designed back in 1857 by Lambert Cowell to be used in teaching of swimming strokes (Colwin, 1999). It consists of a bench for the swimmer to lie on and a pulley system which offers semi-accommodating resistance[1] (Heusner, 1980). It is also equipped with a speed-controlling mechanism that accelerates to a set constant velocity. This acceleration is possible throughout the full range of motion (Thornton and Flavel, 1977). The swimmer pulls on pulley-ropes and the resistance elicited from the apparatus is designed to match the resistance experienced during actual swimming at any given point in the range of motion of the muscle groups being exercised. This resistance is provided by a shunted generator[2] and is electromagnetic, not frictional[3]. A built-in electronic read-out unit records the force produced and the distance by which the pulley-rope is extended, thus enabling the mechanical work performed to be measured (Councilman, 1980). The analogue output on the 'biokinetic' (Biokinetics is a trade mark of Isokinetics, Inc.) swim bench drives a high-speed chart recorder to produce permanent record of stoke and force characteristics (Thornton and Flavel, 1977). A diagram of the 'biokinetic' swim bench is shown in Diagram 5.

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[1] Semi-accommodating resistance seems to combine the best features of both the variable resistance (i.e. resistance matches the shapes of typical human strength curves throughout specified ranges of movement) and accommodating resistance (i.e. resistive force varies automatically so as to be continuously equal and opposite to any applied muscular force) modes.

[2] The shunted generator allows the subject to generate their own electromagnetic resistance. The wear of the generator's parts is negligible as any heat generated by usage is dissipated by four purpose-installed transistors.

[3] Frictional resistance is subject to wear and tear. A necessary adjunct to frictional resistance is heat build-up.

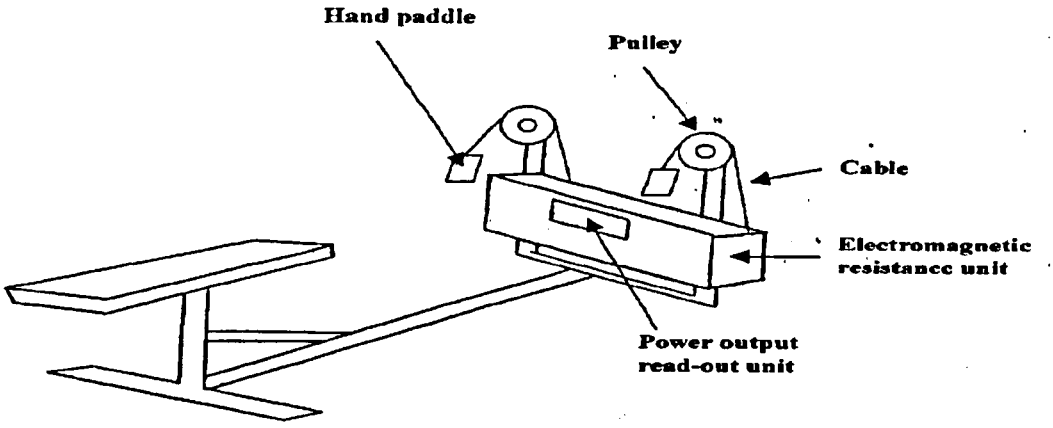

Diagram 5. The 'biokinetic' swim bench showing the pulley system, the hand paddles, the analogue power output recorder and the connection to the electronic unit. Based on Flavel (1980).

Recent developments in swim bench structure (H. and M. Engineering, Gwent, Wales, UK) have added a transducer unit with an interfaced microprocessor. This new swim bench design has allowed physiological measures, such as oxygen uptake ($\dot{V}O_2$) to be related to given power outputs (Swaine and Zanker, 1996). Resistance to the application of tension is such that the pull-rope pays out a velocity, which ranges up to a pre-set maximum. This has termed maximal pull velocity (MPV; Sharp et al., 1982). The resistance unit offers seven settings (range: 0-6) of maximum pull velocity on a continuous scale. Being computer-interfaced, this 'advanced' swim bench offers the opportunity to assess power output at different exercise intensities (Swaine and Zanker, 1996; Swaine, 1997). This has been made possible using a specially designed computer program (H.K. Smith, University of Sunderland). This program receives the numerical data from the interface unit and converts it into a power output reading displayed on screen of an IBM compatible computer, whilst the swimmer is exercising. Further details of this computer program are given in Chapter 2. Subjects have to adopt a prone posture and pull on the hand paddles with alternating arms to replicate the front crawl stroke. They are secured to the bench by a suitably mounted

strap around the torso to restrain movement of the lower body when exercising the arms. The way the subject is exercising on the interfaced swim bench is shown in Plate 1.

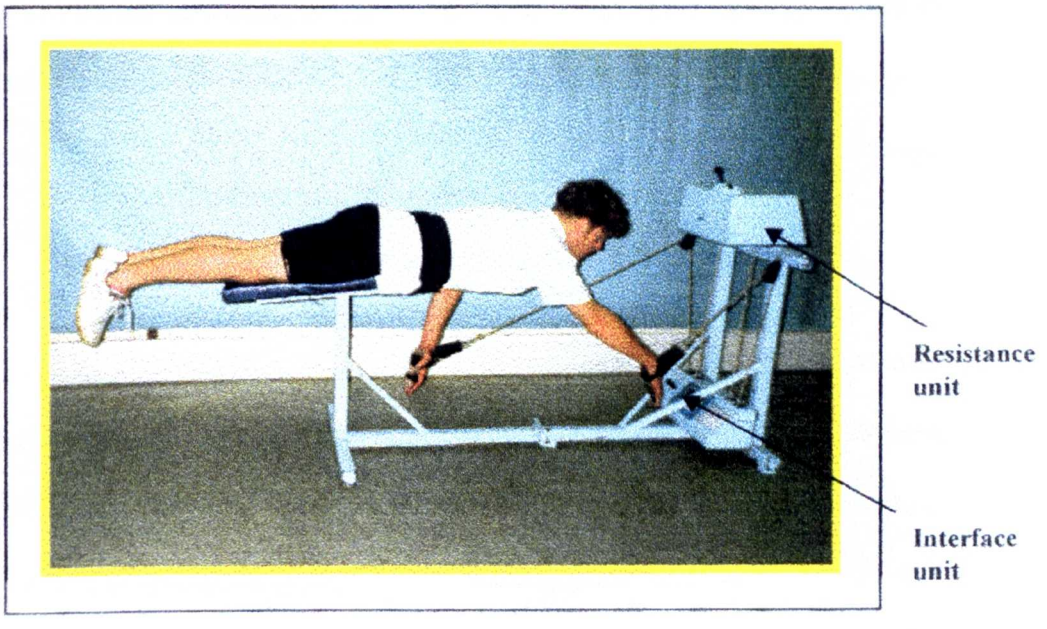

Plate 1. The 'advanced' swim bench showing the resistance and interface units.

There have been many reasons for which the use of the swim bench in strength training of swimmers has been advocated. Research findings have indicated that high-speed strength training on the swim bench significantly increases the strength of swimmers (Councilman, 1980) and improves swimming performance (Pipes, 1978). It has been documented that, although it cannot duplicate the arm and hand actions executed in the water, nevertheless the swim bench allows the swimmer to incorporate (in one motion) most of the muscle groups and the mechanics required during swimming (Costill et al., 1985). Also, the resistance the swim bench offers provides an effective training overload that can increase muscle strength specific to swimming (Pipes, 1978; Sexsmith et al., 1992). Such research set the basis for a series of measurements to monitor improvements in performance when using the swim bench as a training aid (for the improvement of strength).

Similarly, there have also been reasons for which the use of the swim bench in swimming research has been favoured. First, the measurement of power output is one of the main advantages of the swim bench (Swaine and Zanker, 1996). This is potentially useful in physiological assessment of swimmers for the same reasons as have been previously demonstrated in assessments involving the use of cycle ergometry for cyclists (Coyle et al., 1991). There have been studies that have assessed upper and lower limb external power output using arm-cranking and cycling ergometry, thereby enhancing the understanding of the role of power in swimming (Reybrouck et al., 1975), but these types of ergometers have been shown to have poor specificity with swimming (Gergley et al., 1984). Some water-based investigations have assessed propulsive power and force (Toussaint et al., 1988), but these findings can not be compared to power output of the exercising limbs. In addition, the design of swim benches with electromagnetic resistance has facilitated the measurement of muscular power in a pulling action similar to that of free swimming (Reilly et al., 1990). Such measurements cannot be performed using water-based swimming ergometry.

Another advantage in the use of the swim bench for assessment of swimmers is that physiological measurements from this ergometer might not be so dependent on 'swimming technique' as those measurements during swimming itself. The great variation in 'swimming technique' (all factors associated with neuromuscular co-ordination and effective use of force to gain forward propulsion) can confound water-based assessment and this becomes especially apparent in physiological assessment in the swimming flume (Toussaint and Hollander, 1994). More proficient swimmers can sustain increasing water velocities more easily than less proficient or novice swimmers through their enhanced motor co-ordination and skill. This might limit the ability of less proficient swimmers to achieve maximal oxygen uptake ($\dot{V}O_{2max}$). Propulsion is not assessed on the swim bench and for this reason, swim bench testing may be more suitable for physiological assessments in swimmers with poor swimming technique.

The swim bench has been recognised as a versatile method in physiological testing of swimmers (Kimura et al., 1990). However, the extents to which physiological responses derived from the use of this ergometer reflect those of swimming itself have been questioned. The first and major disadvantage of this ergometer is that it cannot be used in the water. Also, it has been demonstrated -in a biomechanical study- that the arm-pulling action performed on the swim bench does not exactly replicate that of actual swimming (Olbrecht and Clarys, 1983). It has been suggested that certain alterations should be made in swim bench design to approximate more the characteristics of actual swimming.

Another obvious criticism has been that the swim bench is used solely to assess the responses to arm-pulling exercise. It has not been possible to assess the responses to leg-kicking using this equipment. In many instances the use of the swim bench, and indeed, the assessment of upper body responses to exercise in swimmers, has been justified on the basis of the perceived contribution of the arms and legs to the overall physiological responses to swimming. It has been previously suggested that leg action contributes very little to overall propulsion in front crawl (approximately 11%; Hollander, 1986). However, there is a need to assess the physiological responses to leg-kicking using direct measurements. Indeed, recently efforts have been made to address this problem, although new developments are only in their early stages (Swaine, 1997).

A disadvantage in current swim bench design is associated with the adopted posture when using this ergometer. The swimmers are requested to adopt a prone position on the swim bench to replicate the front crawl arm-pulling action. It has been suggested that this posture may cause compression of the thoracic cavity, which in turn may restrict breathing (Swaine and Reilly, 1983). This might have implications for performance at high exercise intensities. Moreover, the fixed position of the bench allows very little lateral movement of the trunk and hips during arm-pulling when

using the swim bench. Consequently, swim bench exercise allows limited body roll, which might influence the results of physiological measurements.

1.5. Physiological responses to exercise in swimmers

1.5.1. Physiological responses to exercise in swimmers using water-based ergometry

The physiological responses to swimming have been assessed primarily using various water-based methods. One of these methods has involved the use of tethered swimming to assess the propulsive forces generated by the swimmer. In particular, studies that have used tethered swimming have assessed intra-cycle power variation (Alves et al., 1994), the effects of weight assisted dry-land strength training (Trappe and Pearson, 1994) and force and power during front crawl swimming (Costill et al., 1986). Tethered swimming has also been used to assess physiological and physical correlates of swimming performance (Klentrou and Montpetit, 1991), energy expenditure (Costill et al., 1985) and $\dot{V}O_{2max}$ (Bell and Ribisl, 1979). Since these studies have assessed the responses to whole-body exercise, they are of little value in advancing the understanding of such concepts as the contribution of the arms and legs to the overall (whole-body) physiological responses to exercise in swimmers.

Another type of water-based ergometry has involved the use of the MAD system to investigate the active drag forces generated by swimmers whilst swimming (Hollander et al., 1986). One study using this method investigated the 'technique' and energy losses in front crawl swimming (Berger et al., 1997). The findings of this study suggested that one of the processes that plays a role in swimming propulsion might be the generation of vortices. In another study by Kolmogorov et al. (1997) the hydrodynamic characteristics of competitive swimmers of different genders and performance levels were assessed. It was postulated that the most important factor for reducing active drag is improved biomechanical 'technique'.

Studies that have used tethered swimming have compared peak oxygen uptake ($\dot{V}O_{2peak}$) in tethered swimming and cycling (McElveen, 1986) and in tethered and free swimming (Conley et al., 1991; Conley et al., 1992; Rinehardt et al., 1991). However, the weakness of tethered swimming is that its design allows for assessment of active drag of the arms only. Therefore, it could not be used in assessment of the responses to leg and combined arm-leg exercise.

Toussaint and Vervoorn (1990) measured the effects of specific high resistance training in the water, using an adaptation of the MAD system called fixed POP (Push Off Point). It was concluded that POP is a suitable device for increasing maximal power output during swimming. However, this system assessed the propulsive forces generated by the whole-body during swimming. Consequently, these findings can not be used to draw any meaningful conclusions on the power developed by the arms and legs separately during whole-body swimming.

Another water-based method in physiological testing of swimmers has involved the use of the swimming flume (Åstrand and Englesson, 1971). This method has allowed determinations of physiological variables such as oxygen uptake, $\dot{V}O_{2max}$ and pulmonary ventilation in relation to swimming velocity. In particular, there have been studies which have included assessment of the relationship between oxygen uptake, stroke rate and swimming velocity (Wakayoshi et al., 1995), determinations of critical speed (Wakayoshi et al., 1993), active drag (Niklas et al., 1993) and oxygen intake dynamics during step-by-step loading (Kipke, 1978). Also, there have been studies that have compared swimming flume physiological measures with respective measures during tethered and free swimming (Bonen et al., 1980). However, it has not been possible to compare directly the physiological responses to arms- and legs-only exercise during whole-body swimming at different water velocities using this equipment.

1.5.2. Physiological responses to exercise in swimmers using dry-land ergometry

Apart from the aforementioned water-based methods, there have also been dry-land methods in assessment of physiological characteristics of swimmers. One of these methods has involved the use of the swim bench. Studies that have employed swim bench testing have included determinations of cardiopulmonary responses to exercise (Swaine and Zanker, 1996), adaptations to training using surgical tubing (Sexsmith et al., 1992), $\dot{V}O_{2max}$ (Meerloo et al., 1987), anaerobic power (Takahashi et al., 1992) and also ergometric analysis of age group swimmers (Armstrong and Davies, 1981).

Furthermore, swim bench measurements have been compared with measurements of swimming performance. These studies have related physiological variables to middle-distance swimming performance (Swaine, 1994), and arm power to sprint swimming performance (Sharp et al., 1982). Also, oxygen uptake (Ogita and Taniguchi, 1995) and bioenergetic characteristics (Obert et al., 1992) from swim bench and water-based testing have been compared. Swim bench measurements have also been compared with tethered and flume swimming measurements. These studies have investigated the relationship between tethered and swim bench $\dot{V}O_{2max}$ (Kimura et al., 1990). Other studies have compared critical speed as measured using flume swimming with critical power as measured during swim bench exercise (Toussaint et al., 1998).

The usefulness of swim bench measurements has also been evaluated in relation to training. These studies have determined the effects of swim bench training (Roberts et al., 1991), intense swimming training (Obert et al, 1996), arm training (Gergley et al., 1984) and training using hand-paddle aids (Ogita and Taniguchi, 1995). Swim bench measurements have allowed quantification of arm power output in relation to exercise intensity (Swaine and Zanker, 1996). However, the design of the swim bench has not allowed measurement of leg-kicking power output and thus, swim

bench findings can only have implications for the training of the arms in swimming. However, the recent developments of Swaine (1997) have introduced a novel type of leg ergometry for swimmers. A full description of this new ergometer is given in Chapter 2 (see section on Ergometers).

1.5.3. Comparisons of physiological responses to swimming using different assessment methods

In the physiology of swimming literature, there have also been studies that have used comparisons of different water-based and dry land methods in assessment of physiological responses to exercise in swimmers. Power output has been one of the physiological characteristics that have been assessed. One study compared swimming and propulsive force during swimming in a flume with power output using external weights (Klauck and Ungerechts, 1997). In this study, propulsive force was measured in the swimming flume and was compared to the power output through use of external weights. It was suggested that there is a high correlation between the propulsive forces the swimmer can generate during swimming and the power of swimmer on land. However, these measurements assessed the propulsive force of the whole-body and not the separate propulsive force of the arms or the legs.

Other studies have used different methods to measure muscular power of swimmers. Costill et al. (1985) reported the effects of reduced training on muscular power using three different assessments. These researchers compared the effects of tapering on muscular power as measured on a swim bench and during tethered and free swimming. It was shown that improvements in power output due to tapering were reflected in the swim bench measurements and in the free swimming power tests. Nevertheless, this study compared whole-body water-based power to arms-only swim bench power.

1.6. Physiological responses to arm versus leg exercise

Since the earliest reports of studies of physiology of exercise in the 1920s, research groups have mainly sought to investigate the physiological responses to exercise that involved participation of lower body muscle groups. Until the late 1960s, there were very few studies that had elaborated on the responses to upper body exercise (Asmussen and Nielsen, 1946; Asmussen and Hemmingsen, 1958). Nevertheless, an early study had identified a higher physiological strain during arm than during leg exercise performed at the same metabolic rate (Collett and Liljestrand, 1924). Despite such intriguing findings, research interest was only drawn into this area in the beginning of 1970s (Reilly et al., 1990).

In the past thirty years, the study of physiological responses to upper versus lower body exercise has experienced a resurgence. This increased interest has stemmed from the recognition that upper body muscle groups are used to perform a variety of industrial (Ford and Hellerstein, 1958) and military tasks (Sawka et al., 1984) apart from sports activities (Gergley et al., 1984). Primarily, the importance of arm and leg exercise has been investigated in relation to sport and exercise to optimise performance and aid the conditioning and rehabilitation of athletes (Gutin et al., 1988). In addition, areas of human physiology such as 'clinical physiology' have focused upon studying the responses to arm versus leg exercise to aid rehabilitation and physical conditioning of patients. The responses to arm versus leg exercise have been studied in wheelchair athletes (Curtis, 1981), paraplegics (Davis et al., 1990; Barstow et al., 2000), patients with claudication (Walker et al., 2000), multiple sclerosis sufferers (Ponichtera-Mulcare et al., 1995), individuals with spinal cord injury (Figoni and Glaser, 1993), and coronary heart disease patients (Åstrand, 1972). Furthermore, in 'space physiology' the responses to arm exercise have been studied at different postures to account for the weightless state astronauts experience in space (Gazenko et al., 1980).

The assessment of physiological responses to upper or lower body exercise in the different sports has mainly involved the use of arm-cranking and cycling ergometry. Studies have investigated the cardiorespiratory responses to prolonged arm and leg exercise (Aminoff et al., 1997), the energy expenditure and heart rate responses to three modes of stationary cycling (Melanson and Freedson, 1995) and the influence of posture and speed of arm and leg work on physiological responses (Kumar, 1982). Another method has involved the use of hand weights during stationary cycling (Auble and Schwartz, 1991; Sagiv et al., 1991). Even though these studies have related their findings to oxygen uptake or exercise intensity, they have little relevance to swimming since the ergometry used has been documented to have poor specificity with swimming (Gergley et al., 1984).

There have also been studies that have investigated the physiological responses to combined arm-leg exercise. These studies have mainly assessed gas exchange measures, such as oxygen uptake and minute ventilation and have used arm cranking and cycling ergometry (Reybrouck et al., 1975; Toner et al., 1986) and more recently an arm-cranking air-braked ergometers (Hoffman et al., 1996; Nagle et al., 1984). One of the greatest issues in the physiology of swimming is the relative contribution of the arms and the legs to the overall physiological responses to exercise, when they are being exercised simultaneously during whole-body swimming. There have not been any studies that have assessed the physiological responses to arm and leg exercise during whole-body swimming in this way.

Perhaps, one of the main aims of studying arm versus leg exercise is to identify possible differences or similarities in the physiological responses to upper and lower body exercise. One of the main reasons behind such research is to seek more effective ways to prescribe exercise recommendations for those sporting activities that primarily engage arm (canoeing, kayaking) or leg exercise (running, cycling) and also activities that engage a combination of arm and leg exercise (swimming, gymnastics). There have been many research studies that have focused on identifying differences

or similarities in the physiological and metabolic responses to arm and leg exercise. An extensive discussion of the main findings is provided in the following section.

The physiological responses to arm versus leg exercise have been investigated in relation to oxygen uptake, heart rate, pulmonary ventilation and also blood pressure and metabolism. The main findings of such research are presented below.

1.6.1. Oxygen uptake responses to arm versus leg exercise

Some of the key studies of the physiological responses to arm or leg exercise in general have used assessment of the oxygen uptake responses to arm or leg exercise at the same exercise intensities or at the same metabolic rates (Pendergast, 1989). One of the main findings of such research was that the highest oxygen uptake ($\dot{V}O_{2max}$) achieved during arm exercise is generally about 20-30% lower than the highest oxygen uptake achieved during leg exercise (Hesser et al., 1977; Magel et al., 1978; Miles et al., 1989). These differences in $\dot{V}O_{2max}$, which have been observed for in both men and women (Warren et al., 1990), have been attributed to the smaller muscle mass of the arms. It has been documented that the demand for energy is lower in the arms when compared to the legs due to the larger muscle mass of the legs (Blomqvist et al., 1982; Blomqvist, 1985).

In submaximal exercise, however, the response pattern is somewhat reversed (McArdle et al., 1991), where oxygen consumption, as a function of exercise intensity, is higher during arm than leg exercise (Toner et al., 1983; Vander et al., 1984; Hagerman, 1988; Pendergast, 1989). This greater physiological strain in submaximal arm compared to leg exercise is attributed to the lower mechanical efficiency associated with the static (no external mechanical work produced) muscular contractions during arm-cranking exercise (McArdle et al., 1991). It has also been suggested that this form of work requires extra musculature to stabilise the torso (Clausen and Trap-Jensen, 1976; Schwade, 1977). More recently, Faria and

Faria (1998) used arm rowing and leg extension exercise and postulated that cardiorespiratory responses to upper body exercise do not differ significantly from those to lower body exercise, so long as the upper and lower body workloads are set at an equal relative strength level. These workers stated that, although power output for leg extension was 144% higher than in arm rowing exercise, the mean oxygen uptake for arm rowing exercise was not significantly different than the respective value for leg exercise. Swaine (1997) compared the oxygen uptake responses to arm and leg exercise using a swim bench and a leg-kicking ergometer, the mean $\dot{V}O_{2peak}$ and EI_{peak} for arm-stroke represented 85% and 88% respectively of the same measures for leg-kicking. The results of this study showed that highly trained swimmers can achieve similar peak levels of oxygen consumption when using the arms or the legs. It appears that the differences in oxygen uptake response to submaximal arm and leg exercise may differ depending on the type of exercise mode used. Furthermore, Turner et al. (1997) suggested that due to infrequent use and a lack of load-bearing function, arm muscle volume is underdeveloped in untrained, sedentary or detrained and injured subjects and for this reason maximum aerobic capacity might be inhibited in the arms.

1.6.2. Heart rate and pulmonary ventilation responses to arm versus leg exercise

It has been documented that the maximal values for heart rate and pulmonary ventilation are lower with arm compared to leg exercise (Vokac et al., 1975; Schwade et al., 1977). However, an adjustment should be made in estimating maximum heart rate if swimming or other forms of arm exercise are used (Franklin, 1989). Maximum heart rate in these exercise modes averages about 10-13 beats · min^{-1} lower than running in both trained and untrained subjects (Vander et al., 1984; Magel et al., 1975; McArdle et al., 1979). As noted previously for oxygen uptake, this difference is probably the result of a relatively smaller muscle mass being activated in upper body exercise such as arm-cranking and swimming compared to running or cycling

(McArdle et al., 1991). These findings are consistent with other studies investigating blood flow where the majority of data suggest that blood flow is primarily directed to larger muscles masses during heavy exercise and leg blood flow is not compromised when arm exercise is added to leg exercise (Harms, 2000). With swimming, the horizontal body position and the cooling effect of immersion in water may also be factors that contribute to lower maximum heart rate (McArdle et al., 1996).

In submaximal exercise, heart rate responses are generally higher during arm compared to leg work (DeBusk et al., 1978). It has been suggested that dynamic arm exercise results in more rapid withdrawal of vagal outflow than dynamic leg exercise and this condition persists even after administration of beta-adrenergic blockade (Tulppo et al., 1999). The same workers noted that the vagally mediated beat-to-beat R-R interval fluctuation decreased until the level of approximately 50% of maximal oxygen consumption during an incremental cycle exercise test. Tulppo et al. (1999) compared the changes in autonomic modulation of heart rate during arm-cranking and leg-cycling exercise and concluded that the mean heart rate was significantly higher during submaximal arm work than during submaximal leg work. These findings were contradicted by another study that investigated whether the central command signal associated with isometric exercise is mass dependent (Franke et al., 2000). This study used isometric exercise bouts of 20% of maximum voluntary contraction (MVC) for arm and leg exercise. The findings showed that heart rate was higher during leg than arm exercise. It was suggested that muscle mass influences the central command signal during isometric exercise and central command modulates this response in larger muscle masses (i.e. legs versus arms). However, in the latter study the % of MVC used might have influenced the heart rate responses in that 20% of arm MVC may not correspond to 20% of leg MVC.

1.6.3. Blood pressure responses to arm versus leg exercise

The maximal responses for systolic and diastolic blood pressure follow the response pattern of the cardiorespiratory responses with regard to arm and leg exercise

(McArdle et al., 1996). Conversely, at a given percentage of maximum oxygen uptake, systolic and diastolic blood pressures are considerably higher when exercise is performed with the arms than with the legs (Åstrand et al., 1965; Pendergast, 1989; Toner et al., 1990). The smaller muscle mass and vasculature of the arms seem to offer greater resistance to blood flow compared to the larger muscle mass and vasculature of the legs (Blomqvist et al., 1982). During arm exercise the work of the heart increases considerably and thus, there is greater cardiovascular strain (Miles et al., 1989). For these reasons, the use of arm exercise for individuals who have any type of cardiovascular dysfunction is not recommended (McArdle et al., 1996).

1.6.4. Metabolic responses to arm versus leg exercise

There have been a few studies that have compared the metabolic responses to arm and leg exercise. These studies have mainly used arm-cranking and leg-cycling exercise. Some of these studies have compared the metabolism of arms versus legs at relative exercise intensities of $\dot{V}O_{2peak}$ (Alborg and Jensen-Urstad, 1991; Jensen-Urstad et al., 1993; Kang et al., 1997; Aminoff et al., 1998). Alborg and Jensen-Urstad (1991) used arterial and venous catheterisation and blood flow measurements to compare arm and leg metabolism at relative intensities of 30, 50 and 80% of $\dot{V}O_{2peak}$. Even though the absolute exercise intensities were 2.5-3.0 times higher during leg than during arm exercise, arterial lactate concentration was 50% higher for arm exercise at both 30% and 50% of $\dot{V}O_{2peak}$ and the same as leg lactate output at 80% $\dot{V}O_{2peak}$. Arm lactate release was 3 times higher or the same as leg lactate release at the same corresponding exercise intensities. Alborg and Jensen-Urstad (1991) concluded that exercising arm compared to leg muscles working at the same relative intensities utilise more carbohydrate (mainly muscle glycogen) resulting in higher lactate release by the exercising extremity. Jensen-Urstad et al. (1993) investigated the differences in metabolic responses to arm and leg exercise corresponding to 60% of $\dot{V}O_{2peak}$ and concluded that arm exercise is associated with greater release of blood lactate and blood ammonia $[NH_3]^+$. These results indicated a

more severe metabolic strain during arm exercise, which relates to the higher cardiorespiratory strain (i.e. the rate of oxygen consumption in relation to exercise intensity) also experienced during arm exercise compared to leg exercise, which has been discussed in a previous section. Kang et al. (1997) compared the metabolic efficiency at relative exercise intensities corresponding to 50, 60 and 70% $\dot{V}O_{2peak}$ and suggested that metabolic efficiency of the arms is lower than that of the legs at all of these relative exercise intensities. Although, however, the metabolic efficiency is lower during submaximal arm than leg exercise the metabolic strain (i.e. the rate of blood lactate increase in relation to exercise intensity) is higher (Jensen-Urstad et al., 1993). Aminoff et al. (1998) compared arm and leg exercise at 50% and 75% of $\dot{V}O_{2peak}$ for the corresponding muscle group. It was shown that blood lactate concentration was higher after arm exercise than after leg exercise; at the 50% exercise level the difference was statistically significant. These results indicated a higher metabolic strain during arm than during leg exercise at the same muscle group-specific relative work load.

Another study investigated whether the differences in the metabolic responses to arm and leg exercise are influenced by the training status of the arm muscles (Jensen-Urstad and Alborg, 1992). This study used arm-trained and arm-untrained subjects and compared arterial lactate concentration after 30 minutes of arm-cranking and leg-cycling exercise. These workers showed that, in both arm-trained and arm-untrained subjects, arterial lactate concentrations were 27-60% higher during arm than during leg exercise and that lactate release from the exercising limbs was 2-4 times higher during arm compared to leg exercise. Jensen-Urstad and Alborg (1992) confirmed previous findings that arm exercise is associated with a larger lactate release compared to leg exercise and postulated that this difference can be influenced only to a minor extent by intense training of the arms. They also suggested that the high arm versus leg lactate release appears to be associated with differences in regional circulatory adaptations by the exercising limbs.

1.6.5. Physiological responses to arm and leg exercise in swimmers

In swimming, the study of physiological responses to arm versus leg exercise would provide insight into the different physiological demands of these two components. It has been previously suggested that maximal responses to arm exercise may be hindered due to the limited muscle mass in the upper body in comparison to the lower body muscle mass (Vokac et al., 1975). This theory might be reversed in swimming, where it has been postulated that arm-pulling provides the major contribution to propulsion in comparison to leg-kicking (Hollander et al., 1986). Therefore, it might be useful to investigate the separate contributions of arm-pulling and leg-kicking to the overall physiological responses to arm and leg exercise in swimmers whilst these two body segments are exercised separately and simultaneously. Furthermore, the metabolic contribution of arm-pulling versus leg-kicking to whole-body metabolism when the arms and legs are exercised simultaneously could be investigated. Such findings would highlight the specific training requirements of the arms and the legs and would provide the basis for the design of appropriate training programmes to optimise swimming performance. It might also be the case that such findings might have implications for the physiology of other sports that equally involve the use of the upper and lower body muscle groups, such as water polo, gymnastics and diving.

There have been a few studies that have assessed the differences in the physiological responses to arm versus leg exercise in swimmers. Mainly, these studies have employed arm-cranking or cycling. One of these studies compared arm muscle power with sprint swimming performance (Hawley and Williams, 1991). The findings suggested that arm muscle power, as measured during Wingate anaerobic tests for the upper and lower body, could predict swimming performance. Another study elaborated on the physical fitness of young male Belgian swimmers (Francaux et al., 1987) by measuring the improvements in their power output over a training period. The results of this study showed a progressive adaptation of heart rate, aerobic capacity and mechanical power output for a given work load. However, equipment used for testing in these studies (arm-cranking and cycling ergometry) has been

shown, as mentioned in an earlier paragraph, to have poor specificity with swimming (Gergley et al., 1984).

1.6.6. Physiological responses to arm and leg exercise after training of the arms and the legs in general

Many studies have assessed the physiological responses to upper versus lower body exercise with regard to training. The aim of such investigations was to ascertain the magnitude of adaptations due to training in the physiological responses to arm or leg exercise and accordingly prescribe exercise recommendations for those sports that primarily engage the arms and the legs. Generally, the adaptations due to training include greater maximal oxygen consumption, increased muscular strength, improved neuromuscular co-ordination, greater mechanical efficiency, greater maximal cardiac output and capability to perform work at a lower metabolic cost in the trained segments (McKeown, 1979). Studies have included determinations of pulmonary ventilation (Rasmussen et al., 1975) and cardiovascular responses to upper body exercise (Pendergast, 1985) after training of the arms or the legs. Also, other researchers have investigated the blood lactate responses before and after arm or leg training (Klausen et al., 1974), the transfer effects of endurance training (Bhambani et al., 1991) and the metabolic adjustments to arm training (Magel et al., 1978).

In particular, there have been studies that have investigated the adaptations due to training in the localised metabolism and physiological measures of the arms or the legs. Clausen et al. (1971) investigated the effects of arm-cranking and leg-cycling training on metabolism and pulmonary ventilation. The findings showed that decreases in oxygen uptake, respiratory exchange ratio, pulmonary ventilation and blood lactate were noted in response to arm-cranking training in the arm-trained group, whereas similar decreases were noted in response to leg-cycling training in the leg-trained group. The same workers suggested that limb-specific training brings about limb-specific adaptations. Moreover, Turner et al. (1997) investigated the

effects of endurance training of the same duration for the arms and the legs on oxygen uptake and mitochondrial volume. These workers reported that endurance training of the same duration for the arms and the legs induces similar increases in peak oxygen consumption and mitochondrial volume in leg-trained and arm-trained muscles, respectively.

The effects of arm and leg training on the heart rate responses to arm and leg exercise have also been investigated (Clausen et al., 1970). It was shown that training with arm muscles caused a reduction in heart rate during an arm ergometry test, whereas training with leg muscles caused a reduction in heart rate only during a leg ergometry test. It was theorised that arm training increased the oxidative capacity of the arm muscles and leg training increased the oxidative capacity of the leg muscles with a subsequent reduction in the heart rate responses. These findings set the basis for the 'specificity of training' principle (Strømme et al., 1977) as the change in response due to training is reflected mainly to the specific group exercised.

These findings provided insight into the physiological adaptations of the arms and legs due to arm or leg training, but cannot have any direct implications for the training of swimmers, as the training did not use swimming itself and the assessments were not conducted using swimming-specific ergometry. It has also been suggested previously that a swimmer's aerobic capacity ought to be evaluated during swimming, as the cardiopulmonary response to swimming is much different to that noted in land exercises, such as treadmill running and cycling (Nomura, 1983).

1.6.7. Physiological responses to arm and leg exercise after training of the arms and the legs in swimmers

In swimming, research has mainly sought to investigate the effects of training on physiological responses to whole-body exercise. These studies have used water-based assessments and have included the physiological adaptations due to training of different duration on oxygen uptake (D'Acquisto et al., 1992), the changes in aerobic

power as a result of reduced training (D'Acquisto et al., 1992b) and the physiological adaptations due to swim training in untrained female swimmers (D'Acquisto et al., 1992c). Also, there have been studies that have assessed the effects of dry-land arm training on whole-body swimming performance (Gergley et al., 1984; Tanaka et al., 1993). The effects of arms-only or legs-only training on the physiological responses to arms-only or legs-only swimming have been mostly overlooked.

The absence of studies investigating the effects of legs-only training on the physiological responses to legs-only swimming has been mainly attributed to the traditional theory that the arms contribute more to propulsion than the legs in all swimming styles (Alley, 1952; Adrian et al., 1966; Magel, 1970; Hollander et al., 1988; Toussaint and Beek, 1992). In support of this theory, studies that have compared maximum velocities in arms-only, legs-only and whole-body front crawl swimming have suggested that leg-kicking is the most inefficient part of the swimming movements (Kaprovich, 1935; Bucher, 1974). Other studies have emphasised the importance of increasing arm power with swimming training as it contributes to changes in whole-body swimming performance (Charbonier et al., 1975; Sharp et al., 1982; Costill et al., 1983; Toussaint and Vervoorn, 1990). Furthermore, other studies have suggested that the main function of the leg kick action in front crawl is to keep the body in a streamlined position to reduce drag (Councilman, 1977) and stabilise the trunk (Councilman, 1968; Laurence, 1969). However, none of these studies assessed the effects of leg swimming training on swimming performance.

Conversely, it has been suggested that oxygen uptake during legs-only swimming is higher than during arms-only swimming (Keskinen and Komi, 1992) and peak oxygen uptake during dry-land leg-kicking is higher than arm-pulling (Swaine, 1997). Also, it has been shown, using dry-land ergometry, that the legs can sustain greater power output than the arms during leg-kicking compared to arm-pulling exercise (Swaine, 2000). Furthermore, it was shown, in a study that used

cinematography, that the legs enhanced the generated propulsive force of the whole-body by improving the propulsive action of the arms (Deschodt et al., 1999). These findings indicate that perhaps future research endeavours should concentrate on investigating the adaptations due to arm and leg training in the physiological responses of the upper and lower body of swimmers.

1.7. The need for novel forms of dry-land ergometry and assessment methods in swimming

The need for novel forms of dry-land ergometry and assessment methods in swimming arises from the difficulties associated with water-based testing. These difficulties mainly include practical limitations in the measurement of physiological parameters, such as oxygen uptake, heart rate and blood lactate using tethered or flume swimming. First, the measurement of oxygen uptake ($\dot{V}O_2$) requires the use of a mouthpiece (with headgear attached) and a nose clip. This arrangement, when used in the water, is thought to disrupt the breathing pattern, increase drag and cause alterations in 'swimming technique'. In addition, a safety risk might be associated with the possibility of water inhalation. Second, measurements of muscle capability, such as blood lactate (HLa) are impossible to be performed during continuous incremental swimming.

There are also fundamental research questions that cannot be answered using the existing methods. Investigations into physiological measures, such as $\dot{V}O_2$, HLa, and heart rate (HR) during arms-only versus legs-only exercise are difficult when using the swimming flume, since legs cannot be exercised at the same water velocities as the arms. Similarly, exploration of the relative contributions of the arms and the legs to the whole-body metabolism during whole-body exercise is not possible using either flume or tethered swimming. To answer these 'key' research questions, there is a necessity for ergometry that allows separate measures of arms and legs to be performed whilst these two body segments are being exercised simultaneously as in

free swimming. Such research could enhance the understanding of the differences or similarities in the upper and lower body physiology and muscle capability of swimmers and could have implications for the design of more effective training regimens. Also, concepts fundamental to the understanding of the physiology of swimming such as the contribution of arms versus that of the legs, might be clarified.

1.8. Technological development in dry-land ergometry: a new ergometer that allows quantification of leg power output

The main problem associated with swim bench testing is the absence of information on physiological responses to leg-kicking. There have been studies that have related swim bench measures with swimming performance (Swaine, 1994) and with maximal oxygen uptake during tethered swimming (Meerloo et al., 1988). These studies have reported high correlations, but have not taken into consideration the leg-kicking responses. In addition, swim bench findings have suggested that swimming performance may improve through gains in muscle power of the arms (Obert et al., 1996), but no inferences can be made for any possible improvements in swimming performance through gains in muscle power of the legs. Therefore, current determinations involving the use of dry-land ergometry tend to ignore the leg-kicking component in front crawl swimming. A possible solution to this problem might be found in the development of a new dry-land ergometer.

Indeed, Swaine (1997) has introduced a new dry-land ergometer specially designed to replicate the front crawl leg-kicking action. Such a technical innovation facilitates measurements of power output in response to front crawl leg-kicking. Determinations derived from the use of this new leg-kicking ergometer could supplement swim bench measurements on arm-pulling. This would allow comparisons of physiological responses to arm-pulling and leg-kicking in swimmers. Such comparisons could enhance the understanding of the physiological mechanisms that underlie arm versus leg exercise in swimming.

Findings from studies of the physiological responses to arm-pulling versus leg-kicking might have implications for the training of the arms and the legs in swimmers. Also, there might be a way to use the new leg-kicking ergometer simultaneously with the swim bench to conduct combined arm-leg assessments. It might then be possible to identify the relative contributions of the arms and the legs to the physiological responses to whole-body exercise. Furthermore, it would then be possible to compare physiological responses to dry-land arm, leg and combined arm-leg exercise with respective measures derived from water-based testing. Such a comparison might address some of the criticisms arising from swim bench testing and, consequently, might validate the use of dry-land ergometry in assessment of swimmers.

The developments in water-based and dry-land ergometry for swimmers are summarised in the following table.

Table 1. Time line for significant developments in ergometry for swimmers.

Research	**Year**	**Ergometry**
Åstrand and Eglesson	1971	Swimming flume
Magel et al.	1974	Tethered swimming
Di Prampero et al.	1974	Semi-tethered swimming
Thornton and Flavel	1980	Swim bench
Hollander et al.	1986	MAD system
Costill et al.	1986	Swimming power system
Toussaint and Vervoorn	1990	Push Off Point (POP)
Swaine	1997	Leg-kicking machine

1.9. Aim of studies in this thesis

The aim of the studies presented in this thesis is to evaluate the usefulness of dry-land ergometry in physiological assessment of swimmers. This evaluation will necessarily include the assessment of the usefulness of dry-land ergometry in differentiating between physiological responses in trained and untrained swimmers, assessing the effects of training and the extent to which dry-land ergometry reflects water-based measurements.

1.9.1 Objectives of studies in this thesis

a. To determine whether it is possible to use an incremental exercise protocol to elicit peak oxygen uptake and peak lactate responses to arm and leg exercise when using the arm-pulling and leg-kicking ergometers, respectively.

b. To investigate whether the peak power output responses to arm-pulling are different to those of leg-kicking in trained and untrained swimmers.

c. To ascertain whether dry-land ergometry can detect adaptations due to training in aerobic power and motion economy of the arms and the legs after arms- or legs-only swimming training.

d. To determine whether changes due to training in swimming performance of the arms or the legs are reflected in dry-land measurements.

e. To investigate whether the physiological responses to combined arm-leg, arm-pulling and leg-kicking dry-land exercise compare with whole-body, arms- and legs-only swimming.

f. To determine whether the peak oxygen uptake and peak heart rate responses to incremental combined arm-leg exercise are different to respective responses to arm-pulling or leg-kicking exercise when using dry-land ergometry.

g. To identify some of the limitations that arise from the use of dry-land ergometry, when it is used in physiological testing of swimmers.

h. To outline developments that may improve the use of the existing dry-land ergometry and give directions for future research.

1.10. Summary

Assessment methods in physiology of swimming have primarily involved the use of water-based ergometry, such as tethered swimming, the MAD system and the swimming flume. Even though these methods have enabled a series of physiological assessments to be calculated in the water, there are fundamental research questions, such as the power output of the arms and legs and also the contribution of the arms and the legs to whole-body power output that cannot be addressed using these methods. An alternative approach has involved assessments of physiological responses to arm exercise using a dry-land ergometer, namely the swim bench, which had been initially designed for training purposes. The main weakness of this equipment (i.e. it does not provide for leg-kicking assessments) has recently been overcome through the development of a leg-kicking ergometer.

The study of the responses to separate and combined arm and leg exercise in swimmers might have implications not only for swimming physiology, but also for the physiology of other sports that equally engage the upper and lower body (i.e. gymnastics, diving, synchronised swimming, triathlon). Previous swimming research has primarily used arm-cranking and leg-cycling (Reybrouck et al., 1975) to assess the responses to arm and leg exercise in swimmers, but these ergometers have been shown to have poor specificity in swimming (Gergley et al., 1984). On the other hand, the study of physiological responses to arm and leg exercise using water-based swimming ergometry presents several limitations; namely the difficulties associated with continuous assessments of gas exchange and metabolic measures during swimming. The novel dry-land leg-kicking ergometer that has been recently developed by Swaine (1997) might provide the opportunity for the study of some of the fundamental principles of swimming when this equipment is used in conjunction with the swim bench. Such principles may include determination of the differences or similarities that may exist with regard to arm, leg and also combined arm-leg (whole-body) power output of swimmers.

CHAPTER 2

GENERAL METHODS

This chapter consists of three parts and outlines methods common to the different studies that are presented in the component studies of this thesis. The first part includes description of the different equipment used for analysis of physiological measures, such as oxygen uptake and blood lactate. The second part presents the rationale, method and findings of studies that were conducted to assess the reliability of gas and blood lactate analysis equipment. Finally, in the third part of this chapter, the rationale, method and findings of studies that were conducted to assess the validity of gas and blood lactate analysis equipment are given.

2.1. Dry-land ergometers

2.1.1. The arm-pulling ergometer

As outlined in Chapter 1, recent developments in swim bench structure (H. and M. Engineering, Gwent, Wales, UK) have added a transducer unit with an interfaced microprocessor and a resistance unit as it was shown in Plate 1. The computer-interfaced version of the swim bench comprises a device with two pull-ropes, which drive near-drum resistance devices (spools). Each of the pull-ropes passes through a transducer unit, where the tensile force, the distance through which the force is applied and the duration of force application for each arm stroke are recorded. The internal features of the arm-pulling ergometer's resistance and transducer units are shown in Plate 2.

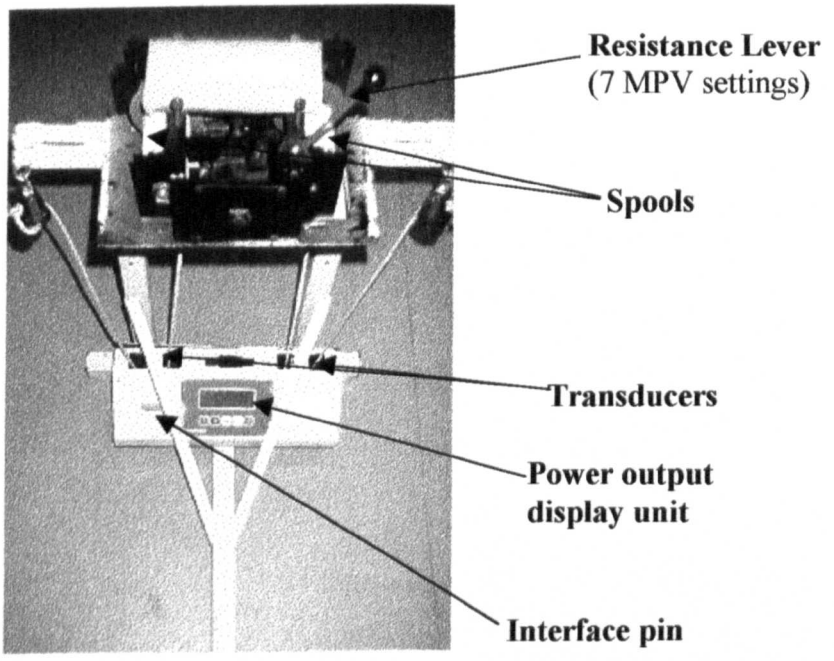

Plate 2. Internal workings of the arm-pulling ergometer (interfaced swim bench) showing the resistance and transducer units.

Being computer-interfaced, this 'advanced' swim bench offers the opportunity to assess power output at different exercise intensities (Swaine and Zanker, 1996). This

has been made possible using a specially designed computer program (H.K. Smith, University of Sunderland) details of which are given in the following section. This program receives the numerical data from the interface unit and converts it into a power output reading displayed on the computer screen, whilst the swimmer is exercising. Subjects have to adopt a prone position and pull on the hand paddles with alternating arms to replicate the front crawl stroke. They are secured to the bench by a suitably mounted strap around the torso to restrain movement of the lower body when exercising the arms.

2.1.1.a. The computer program

This computer program (Diagram 6; H.K. Smith, University of Sunderland) was designed to control the intensity at which subjects exercised throughout arm-pulling tests. It increased the intensity of exercise in small increments and used three exercise protocols: Slow Ramp (7.5 $W \cdot min^{-1}$), Fast Ramp (10 $W \cdot min^{-1}$) and Constant Power. During arm-pulling exercise, the sampled data (100 Hz) were transmitted via an electronic cable to the computer analogue to digital converter and power output was calculated. The computer software was designed to dictate a 'target power' during exercise. The power output that the subject generated during exercise was termed 'actual power'. The value for 'actual power' was shown on a visual display unit on the computer screen by means of a moving cursor. This served as feedback to the exercising subject who could then adjust the power output to match the 'target power'. At 10 W above and below the target power there were dashed lines that defined the 'target power band' within which the subjects had to exercise at all times. The subjects could adjust their power output by manipulating the force, length or rate of their stroke.

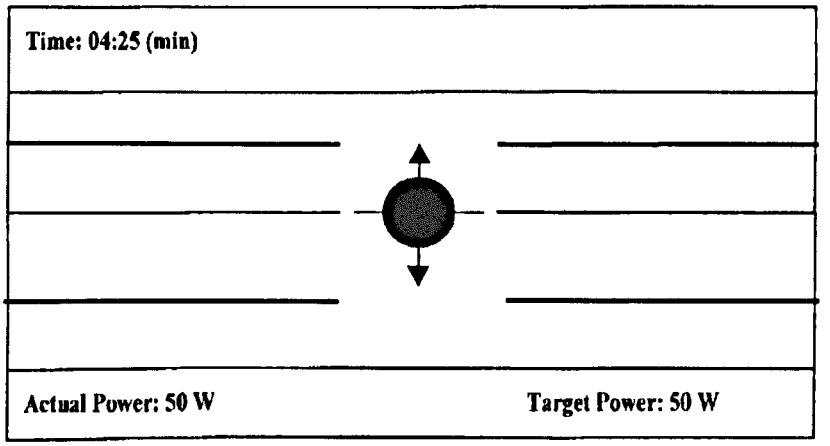

Diagram 6. The computer program. Redrawn from Swaine I.L.: The relationship between physiological variables from a swim bench ramp test and middle-distance swimming performance. *Journal of Swimming Research,* **10:** 41-48, 1994.

2.1.1.b. Computation of 'power output'

Since the force and distance over which the force was computed were sampled at 100 Hz, it was possible to compute instantaneous power output. However, it was observed in preliminary work that such rapid changes in power output were counter-productive, when the swimmers were being asked to adjust their power output to match the 'target power'. It was observed that the most sensitive response times from swimmers were approximately 1-2 seconds within which they could adjust their power output to match the 'target power'. The computation of 'power output' was damped by averaging power readings every 0.5 seconds.

2.1.1.c. Calibration of the arm-pulling ergometer

Calibration of the arm-pulling ergometer was performed periodically (every 6 months) to ensure accuracy of readings at the seven different resistance settings. The calibration procedure of the arm-pulling ergometer has as follows. The ergometer is

set at an upright position. To accelerate the pull-rope until it reaches its maximum pull velocity (MPV; $m \cdot s^{-1}$), the pulleys are arranged so that a heavy weight (500 N) can be attached and allowed to fall to the ground. This weight has been shown to achieve optimum calibration (Swaine and Zanker, 1996). Five pairs of photoelectric timing devices are used to determine the velocity of the falling weight. These are set 0.2 m apart down the path of the falling weight. The time taken for the weight to fall through each 0.2 m section is recorded as the weight breaks the photoelectric timing beams (Swaine and Zanker, 1996). The velocity of the falling weight is then averaged over the four 0.2 m sections, from the measured distance and recorded time. After the initial acceleration (at the start of the falling phase), the falling weight must reach its MPV and then the velocity must remain constant throughout the remainder of the falling phase without showing any signs of acceleration or deceleration. At the same time, the mean measured velocities at each setting are compared to the mean computed velocities from the transducer unit. The calibration is considered successful, if there are no significant differences between the measured and the computed velocities ($P>0.05$). In a repeatability study, the average coefficient of variation (CV%) for within-batch and between-batch velocity measurements was shown to be 2.34% (r=0.91) and 3.21% (r=0.89), respectively. Once the velocity at each resistance setting is ascertained, the relationship between resistance setting (0-6) and MPV is determined. For a successful calibration, the relationship between MPV and swim bench resistance settings has to be inverse linear (Swaine and Zanker, 1996). Once the calibration of the left transducer is satisfactory, the procedure outlined above is used to calibrate the right transducer. The tensile force, pull-rope distance and duration of force readings must be identical for both transducers.

2.1.2. The leg-kicking ergometer

This ergometer is an adaptation of the swim bench (Diagram 7; University of Warwick, Warwick, U.K.) and was designed to make use of the swim bench resistance and transducer units (Plate 3). It allows the exercising individual to use his/her legs and replicate the front crawl leg-kicking action. Two lightweight alloy

wheels (diameter: 20 cm and 30 cm, respectively) are attached on a vertical stantion 1.25 m apart in such a way so that they can rotate freely. The outer rims of the two wheels are then connected with a length of wire cable so that they could rotate in unison 100° either clockwise or anti-clockwise. A wire cable surrounds the two alloy wheels and is interrupted on either side by inverted steel stirrups into which the subject places his/her feet (Swaine, 1997). By use of a pulley system it was possible to pass the pulley-ropes from the swim bench vertically upwards along the length of the wire cable on each side of the ergometer so that they attach to the lower part of the stirrups. This allows the exercising subject to generate power in an upward and downward direction with either foot by flexing and extending the hips and knees. The wire cable allows approximately 15 cm of lateral movement during each kick action. Since the pulley-ropes are attached to the swim bench resistance unit, the computation of power output and the manipulation of the intensity of exercise are similar to that of the arm-pulling ergometer (interfaced swim bench).

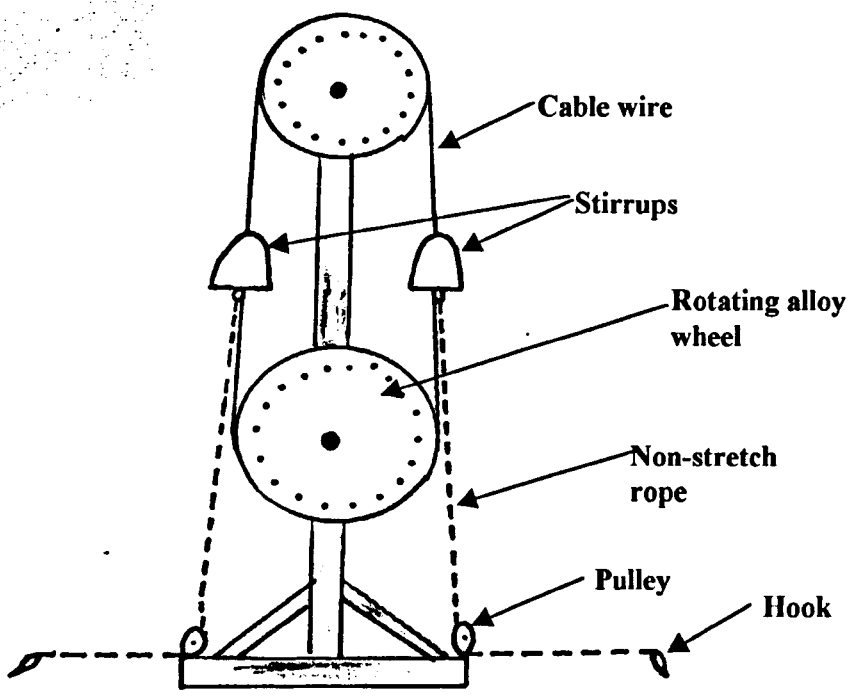

Diagram 7. The leg-kicking ergometer showing the freely rotating alloy wheels and the stirrups into which the swimmer's feet are placed.

This design of the leg-kicking ergometer was used for the purposes of the first study presented in this thesis. Due to safety issues associated with the use of alloy wheels and cable wire, a more lightweight design was later introduced (Plate 3). The alloy wheels were replaced with cycle wheels of the same diameter. The cable wire was substituted by a length of non-stretch rope similar to the one used in the pulley-ropes of the arm-pulling ergometer. Also, the lower part of the metal stirrups was covered with padding to provide a comfortable surface upon which the swimmers could rest their feet without footwear. Furthermore, the leg-kicking ergometer and the resistance unit of another swim bench were fixed on the same platform. This arrangement allowed constant connection of the leg-kicking ergometer to a resistance device. The internal workings of this resistance device, which forms the front part of a swim bench (Model 26E, Fitness Systems Inc., Missouri, USA) are shown in Plate 4. The

improved design of the leg-kicking ergometer was used for the purposes of the second and third studies presented in this thesis.

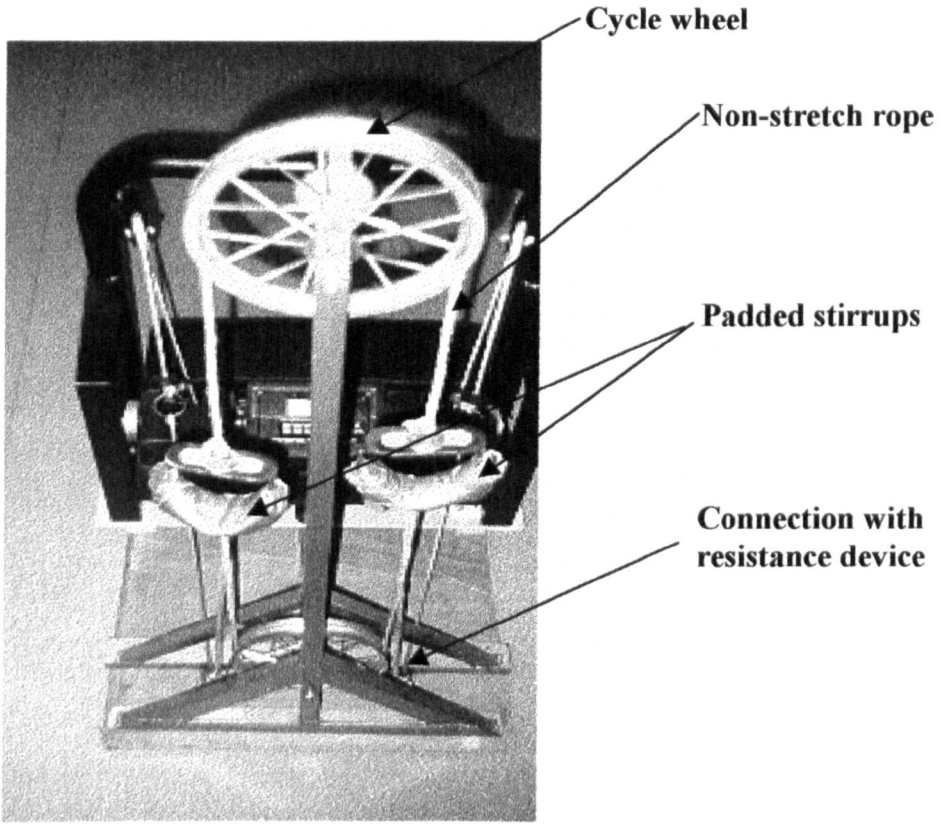

Plate 3. The improved design of the leg-kicking ergometer showing the cycle wheels, the non-stretch rope, padded stirrups and the connection with the resistance unit of a swim bench.

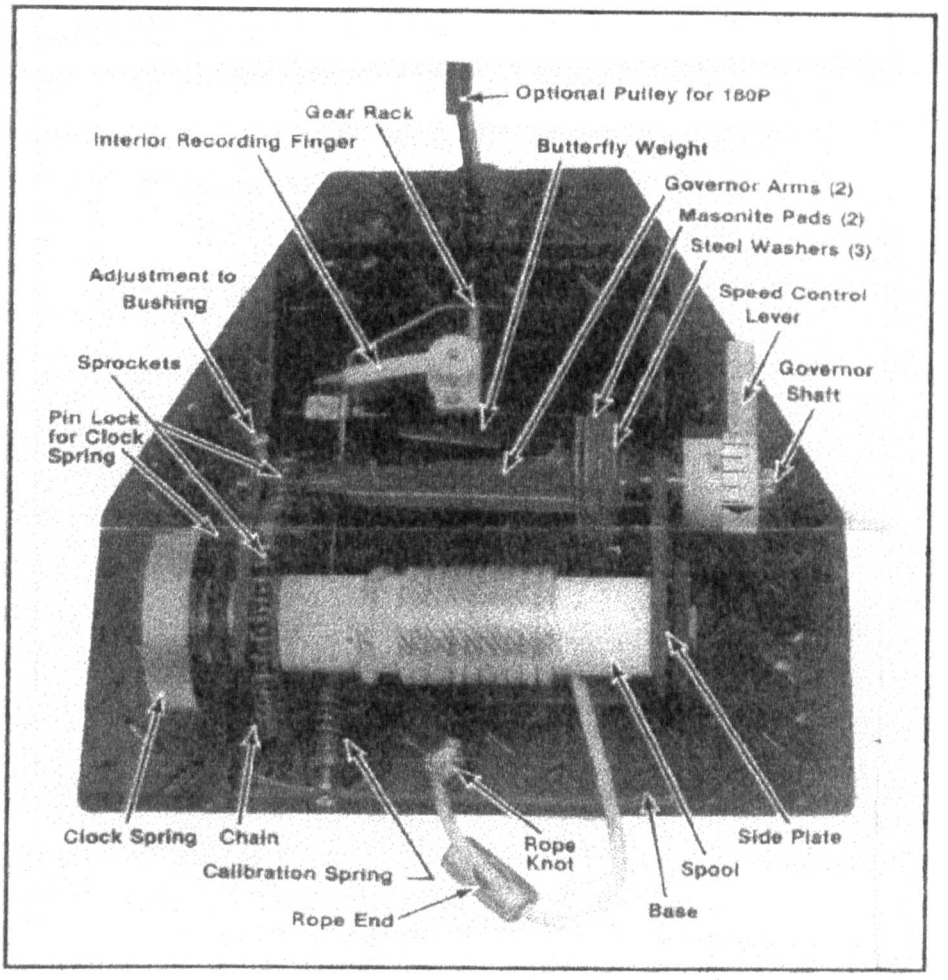

Plate 4. Internal workings of the resistance device that was used with the leg-kicking ergometer (from manufacturer's manual).

2.1.2.a. Calibration of the leg-kicking ergometer

The measurement of power output during leg-kicking exercise was performed through use of the resistance device of the arm-pulling ergometer. The connection of the leg-kicking ergometer to the resistance unit of the arm-pulling ergometer has been described on page 47. Therefore, the same calibration procedure was used for the leg-kicking ergometer as for the arm-pulling ergometer.

2.1.3. The combined arm-leg ergometer

The combined arm-leg ergometer (Swaine et al., 1998) comprises parallel use of the arm-pulling and leg-kicking ergometers (Plate 5). A specially designed platform is used to support the swimmer's torso during exercise. This platform is suspended approximately 1 m from the ground from a purpose-built steel frame. The swimmer adopts a prone posture on the suspended platform and places his/her hands in the hand paddles of the arm-pulling ergometer, which is positioned at an appropriate distance so that to allow elbow flexion during the front crawl pulling action. Simultaneously, the subject places his/her feet in the metal stirrups of the leg-kicking ergometer positioned at a distance that permits knee flexion and extension during front crawl leg-kicking. Using this arrangement the swimmer is asked to pull and kick simultaneously, in an attempt to replicate the full-stroke front crawl swimming action. The intensity of exercise for arm-pulling is increased using the swim bench transducer unit and software as described previously, whereas the intensity of exercise to leg-kicking is set constant using the resistance unit of a second resistance device (as shown in Plate 3). However, the latter arrangement does not allow for increases in intensities of exercise for leg-kicking. Rather, the subjects are simply instructed to increase their leg-kicking rate in relation to the increases in arm-pulling intensity (in a similar way to that expected in free swimming).

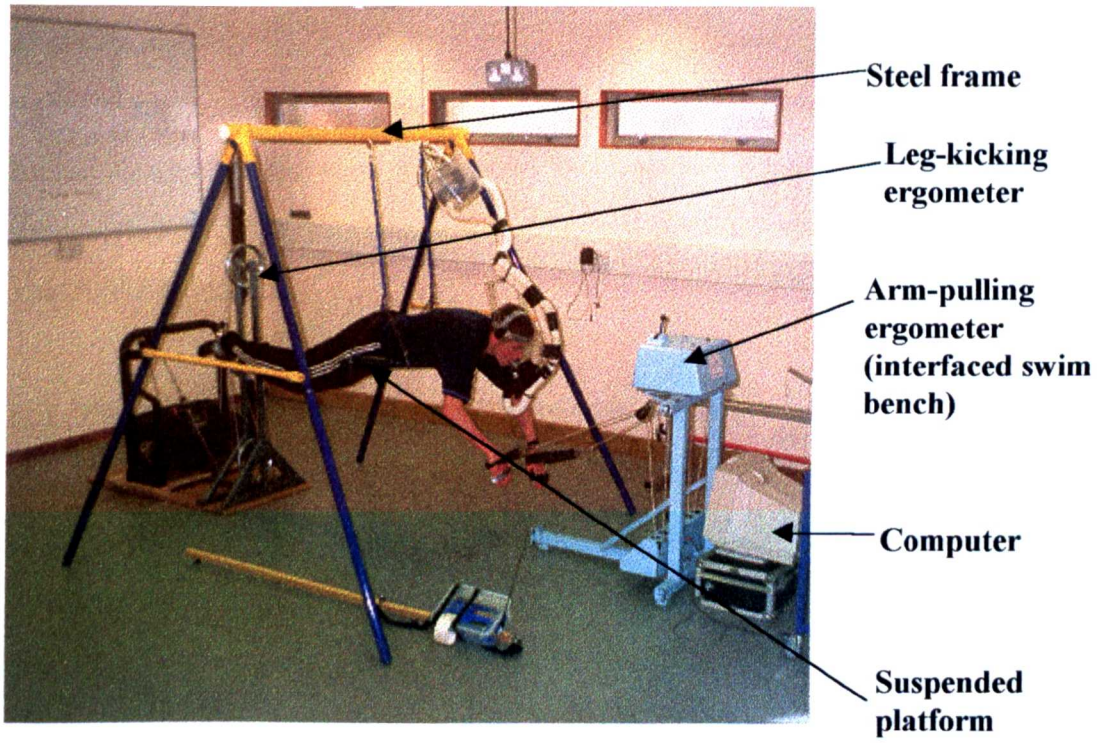

Plate 5. The combined arm-leg ergometer showing the steel frame, suspended platform and the arrangement of the arm-pulling and leg-kicking ergometers.

2.2. Gas Analysis

The main gas exchange measure that was investigated in response to arm and leg exercise using dry-land ergometry in all three studies presented in this thesis was oxygen uptake ($\dot{V}O_2$). The principles of oxygen uptake measurement are discussed in the following section.

2.2.1. Principles of oxygen uptake measurement

The energy (adenosine triphospate; ATP) for physical activities involving prolonged sustained exercise is derived from aerobic metabolism, i.e. the process of disassembling fuels in the presence of O_2 (Wilmore and Costill, 1988). This process takes place in the mitochondria within each muscle fibre where fuels (carbohydrate, fat and protein) and O_2 are disassembled in the presence of specialised proteins called oxidative enzymes (McArdle et al., 1991). The energy bonding the carbon (C), O_2 and hydrogen atoms (H^+) that form the carbohydrate and fat molecules together is liberated by the action of the oxidative enzymes resulting in the formation of ATP (Wilmore and Costill, 1988). Together with the aerobic capacity of the exercising muscle, another major factor in maintaining a high rate of aerobic energy production is the O_2 delivery to the muscles. During this process, the blood picks up O_2 as it passes through the lungs, transports it to the muscles where it is exchanged for carbon dioxide (CO_2), then the blood returns to the heart and lungs to unload CO_2 and refill its O_2 supply (Wilmore and Costill, 1988). Performance in endurance activities, such as long distance running and swimming is thus dependent upon the functional capacity of the O_2 delivery chain (lungs, heart and vascular supply) and the aerobic capacity of the exercising muscle (Rowland, 1996). It has been documented that endurance training improves both the functional capacity of the cardiovascular system (decreased resting and submaximal exercise heart rate, enhanced stroke volume and cardiac output; Åstrand and Rodahl, 1986) and the aerobic capacity of the exercising muscle (increases in mitochondrial size, number, the activity of the aerobic enzymes, the capillarisation of the trained muscle and enhanced oxidation of fat and

carbohydrate; McArdle et al., 1991). An accurate measure of aerobic metabolism can be made by determining the amount of O_2 being consumed, whereas the best single measurement of aerobic endurance and cardiorespiratory fitness is the measurement of maximum oxygen uptake ($\dot{V}O_{2max}$; Wilmore and Costill, 1988). Therefore, the measurement of oxygen uptake ($\dot{V}O_2$) was one of the fundamental concepts in the evaluation of dry-land ergometry in physiological assessment of swimmers.

In this thesis, the measurement of $\dot{V}O_2$ was performed using different equipment (analysers). For the purposes of analysis of expired air (and subsequent computation of $\dot{V}O_2$) using the Douglas bags method (Chapter 2; Reliability and Validity of gas analysis methods), a paramagnetic O_2 and an infra-red CO_2 (Models 1100A and 1490, respectively; Servomex, Sussex, UK) analyser was used. These analysers were used to determine the concentration of O_2 and CO_2 in the expired air collected in the Douglas bags, whereas a computer program (Physiology of Exercise, De Montfort University Bedford, Bedford, UK) was used to compute $\dot{V}O_2$. Other analysers that were used in the different studies presented this thesis were an on-line (COVOX Microlab; Chapters 3 and 4) and a portable, telemetric (COSMED K2; Chapter 5) gas analyser. When using these analysers, it was possible to compute $\dot{V}O_2$ directly. The operation and calibration procedures of these items of equipment are described in the following sections.

2.2.2. Gas analysis equipment

2.2.2.a. The paramagnetic O_2 analyser

This analyser uses a paramagnetic O_2 transducer (Model 1100A, SERVOMEX Ltd., Sussex, UK) that measures the paramagnetic susceptibility of the sample gas by means of a magneto-dynamic type measuring cell[4]. According to the manufacturers, this magneto-dynamic O_2 analyser is based upon Faraday's method of determining the magnetic susceptibility of a gas by measuring the force developed by a strong non-uniform magnetic field on a diamagnetic test body suspended in the sample gas. The test body of all measuring cells consists of two nitrogen-filled Pyrex glass spheres arranged in the form of a dumb-bell. A single turn of fine platinum wire (the feedback coil) is secured in place around the dumb-bell. A rugged, taut band platinum ribbon suspension attached to the midpoint of the dumb-bell positions the dumb-bell in the strong non-uniform magnetic field existing between the specially shaped pole pieces on the permanent magnet structure. The angular position of the dumb-bell is sensed by a light beam projected onto a mirror attached to the dumb-bell from which it is reflected onto a pair of photocells. The difference in the output from these photocells is fed to an amplifier.

When a sample gas containing oxygen surrounds the dumb-bell, the O_2 molecules are attracted to the strongest part of the magnetic field, thus enhancing the magnetic field around the dumb-bell. This changes the force acting on the dumb-bell causing a displacement of the light beam across the photocells, which in turn results in a difference signal being sensed by the amplifier. The resulting output of the amplifier is a current proportional to the O_2 content of the sample, which is fed to the feedback coil of the measuring cell. This produces a magnetic field which opposes the forces causing the dumb-bell to rotate. Thus, the dumb-bell is maintained in its original

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[4] The paramagnetic susceptibility of O_2 is significantly greater than that of other common gases. This means that O_2 molecules are attracted much more strongly by a magnetic field than are molecules of other gases most of which are diamagnetic (repelled by a magnetic field).

position. Since this current is proportional to the O_2 content of the gas sample, it is used to develop the output signal from the analyser. This current feedback force balance design is, according to the manufacturers, resistant to mechanical shock and has outstanding accuracy.

The amplifier accepts inputs from the platinum resistance thermometer, the pressure transducer and the photocells. The signal from the photocells is used to generate the feedback current to the measuring cell and from this a voltage signal which is proportional to O_2 content. The platinum resistance thermometer and the pressure transducer each form one arm of a measuring bridge the outputs of which are amplified. The three analogue signals are fed to the analogue-to-digital converter and hence to the microprocessor.

2.2.2.b. Calibration of the O_2 analyser

The O_2 analyser is switched on and allowed to warm-up for 12 hours for the temperature to stabilise (normal operating temperature was 60 °C). This, according to the manufacturers, contributes to accuracy of measurements and ensures a successful calibration. The gas analyser output meter is calibrated in terms of gas concentration. The calibration is established by standardising with known gas mixtures at one point on the calibrated scale. Two highly compressed calibration gases (BOC Gases Ltd., Surrey, UK) are used to calibrate the O_2 analyser. These gases are span[5] (14.70% O_2, 5.15% CO_2) and zero[6] nitrogen (0.0% O_2, 0% CO_2).

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[5] Span gas: a supply from a cylinder containing a known concentration of the gas to be measured in full sample stream background composition.

[6] Zero gas is a gas mixture containing the full sample stream composition, but with zero concentration of the measured component. In many cases a gas free from infrared absorbing molecules (in this instance CO_2 free nitrogen).

The gas cylinders are fitted with a regulator, whose output could be limited to a maximum 70 kPa (10 psi), to prevent serious over pressuring of the measuring cell. First, the O_2 content of the calibrating gases (zero nitrogen) is introduced into the analyser at a cell flow rate of 100-250 $ml \cdot min^{-1}$ for 2 minutes. When the O_2 reading stabilises, the mechanical zero is checked for being within tolerances (± 2% of zero). The password for zero calibration is entered (the value for this is set by the manufacturers), if the mechanical zero value is within the required limits (otherwise the mechanical zero has to be adjusted before the calibration is repeated). The analyser's response to the password must be be a display of 0.01 77 (77 being the parameter number for zero calibration and 0.01 the status message which indicates a successful zero calibration), as any other values are considered to indicate an error and calibration has to be repeated.

The span calibration is performed after a successful zero calibration. The span gas is introduced into the O_2 analyser at a cell flow rate of 100-250 $ml \cdot min^{-1}$ for two minutes. The O_2 reading is allowed to stabilise and a different password to the one for zero calibration is entered in the key panel. For a successful span calibration, the display must show 001 78 (78 being the parameter number for span calibration and 001 the status message indicating a successful span calibration). Span calibration is repeated, when values other than those intended are displayed.

2.2.2.c. The infra-red CO_2 analyser

The infra-red carbon dioxide analyser (Model 1490, Servomex Ltd., Sussex, UK) is a non-dispersive single beam analyser that measures the quantity of a particular (infrared absorbing) type of gas in a gas mixture. The gas to be measured is passed through an optical cell continuously. Infra-red (heat) radiation from a small source is directed through a rotating gas filter wheel, a collimating lens, a thin-film filter, the sample cell, a focusing lens and on to a solid state detector. The heart of the instrument is the gas filter wheel, which contains a sealed sample of gas of the type to

be measured (in this instance carbon dioxide) and a non-absorbing gas. This rotating wheel provides sample and reference signals sequentially and, together with the selective transmission of the thin-film filter, sensitises the analyser to respond to that region of the infrared spectrum corresponding to the absorption band unique to that gas. When the gas to be measured enters the sample cell, it absorbs some radiation and alters the ratio of the sample and reference signals. It is this change in energy levels that is amplified to give the analyser output signal.

2.2.2.d. Calibration of the CO_2 analyser

Calibration of the CO_2 analyser is performed after the analyser has been switched on and left to warm-up for at least two hours. However, this is usually performed at the same time with the calibration of the O_2 analyser (prior to and after testing) using the separate CO_2 analyser sample gas in-port. The CO_2 analyser is calibrated using zero nitrogen (0% CO_2) and span gas (14.70% O_2, 5.15% CO_2). First, the zero gas is passed through the sample cell in the analyser at a flow rate of 0.5-1.0 $l \cdot min^{-1}$ for two minutes. After this period, the zero control is adjusted to read 0.0 on the meter. The span gas is also passed through the sample cell at a flow rate of 0.5-1.0 $l \cdot min^{-1}$ for two minutes. After this period, the span control is adjusted until the meter reads correctly (i.e. within ±1% of full-scale deflection).

2.2.2.e. Analysis of expired air in Douglas bags

To ensure accuracy of readings, Douglas bags of known volume (120 litres) are evacuated immediately prior to testing using a Dry-Gas Meter (Harvard, MX 230, France). An empty Douglas bag is then connected in-line after the mixing chamber of the COVOX analyser. Expired air is collected for 60 seconds and it is immediately analysed for its O_2 and CO_2 content. This involves the use of the O_2 paramagnetic and CO_2 infrared gas analysers, which is calibrated prior to testing as has been described above. The Douglas bag is attached through its narrow tube to the tubing of the O_2 and CO_2 analysers. Expired air is passed through the analysers for two minutes

exactly, at a flow rate of 1.0 $l \cdot min^{-1}$ and the % O_2 and %CO_2 are recorded. During this procedure, 2.0 litres of expired air are extracted from the Douglas bag. To record the volume of expired air, the Douglas bag is then evacuated using the Dry-Gas Meter. Silica gel is placed at the inlet of this equipment in a cylinder made of perforated zinc. This technique is used to absorb the moisture in the expired air while it passes through the meter. The temperature in the gas cells (T_{gas}; degrees Celsius [°C]) is also recorded through use of a thermometer attached to the dry-gas meter. Barometric temperature (P_{BAR}; mm Hg) is measured using a Fortin barometer (F. Darton & Co., Ltd., London, UK). These data (i.e. %O_2, % CO_2, total air volume, T_{gas} and P_{BAR}) are then entered into a computer program (Physiology Statistics, De Montfort University Bedford, Bedford, U.K.) and oxygen uptake ($\dot{V}O_2$) is computed. The $\dot{V}O_2$ is corrected to STPD (Standard Temperature and Pressure Dry) using the Haldane transformation (Fox et al., 1988).

2.2.3. The COVOX Microlab analyser

The COVOX Microlab analyser comprises on-line gas analysis equipment (COVOX Microlab Pulmonary Systems, Exeter, U.K.; Plate 6) which uses in-built infra-red CO_2 and paramagnetic O_2 analysers. Ventilatory volumes are analysed using an inspired air pneumotachograph (Servomex Ltd., Sussex, UK). Calibration of this equipment is performed prior to every test session and at intervals throughout. This procedure is described in detail on page 65. The expired gases are mixed in a 3-litre chamber and were sampled at pre-set intervals. The computer software that is used with the COVOX Microlab analyser allows manipulation of the sampling interval (5, 15, 30 seconds) in measurement of oxygen uptake and carbon dioxide output.

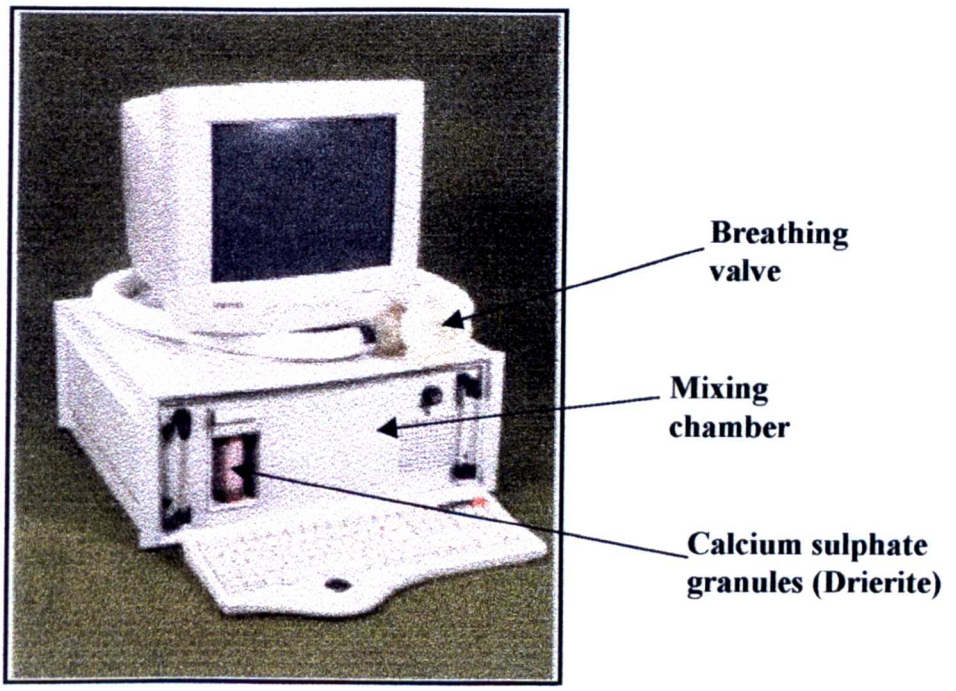


Plate 6. The COVOX Microlab gas analyser showing the mixing chamber and computer.

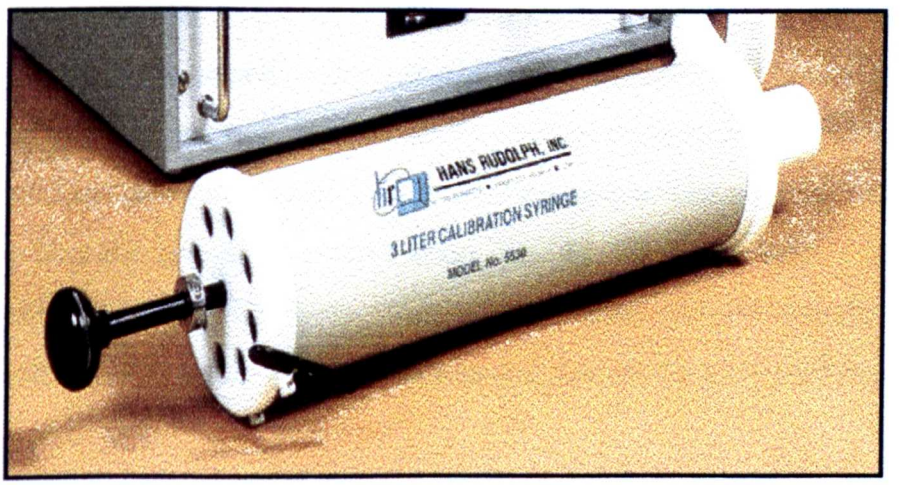


Plate 7. The Hans Rudolf 3-litre calibration syringe used to calibrate the pneumotachometer of the COVOX Microlab gas analyser.

2.2.3.a. Measurement of O_2 concentration

Oxygen concentration is measured using a paramagnetic (paramagnetism is the property of O_2 that distinguishes it from the other gases) in-built O_2 transducer (SERVOMEX Ltd., Sussex, UK). The transducer incorporates an optical system that contained a mirror attached to a suspension mechanism. The suspension mechanism responds to the concentration of O_2 surrounding it by reflecting light from a light-emitting diode onto a split photocell. As the oxygen concentration changes, the light received by each side of the photocell (and therefore its differential output) also changes. According to manufacturer's evaluations, the reported value for repeatability of the paramagnetic O_2 transducer is ± 0.01% per hour.

2.2.3.b. Measurement of CO_2 concentration

Carbon dioxide concentration is measured using an in-built infra-red CO_2 transducer (Servomex Ltd., Sussex, UK). This is based upon a single beam and a single wavelength technique and consists of optical bench supported by control electronics. The gas to be measured is delivered through the sample cell section of the optical bench. An infra-red source generates a signal that is reduced (i.e. attenuated) by the infra-red absorption by the carbon dioxide present in the gas sample. A detection system converts the change of attenuation into an electrical output that is linearised to reflect the concentration of carbon dioxide. The entire optical bench is temperature controlled, thus minimising temperature coefficients and virtually eliminating gas law effects. The reported value for repeatability of the CO_2 transducer is ± 0.1% per 8 hours.

2.2.3.c. Measurement of ventilatory volumes

Airflow is measured using a triple-screen *pneumotachometer* (Hans Rudolf Instrumentation Ltd., Kansas City, USA). This device (Diagram 8) is based on the Fleisch pneumotachograph proportional differential pressure. A capacitance manometer is used to convert the differential pressure into a voltage proportional to

airflow. The measurable range is 0-800 $l \cdot min^{-1}$ producing a maximum back pressure[7] of 7 cm H_2O (mean back pressure[8] during exercise: 1 cm H_2O). The typical signal and back pressures generated by the pneumotachometer are presented in Table 2.

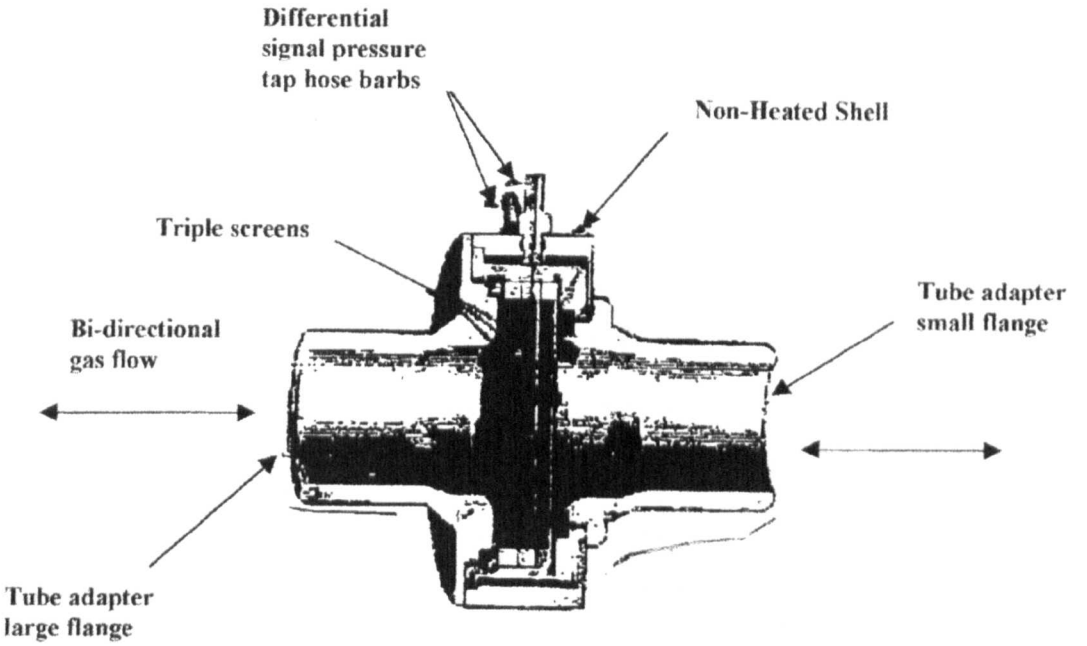


Diagram 8. The Hans Rudolf triple-screen pneumotachometer, showing the triple screens and the direction of gas flow.

[7] Resistance to breathing due to the measuring device.

[8] Resistance to breathing caused by the measuring device due to flow rates in the region of 200 $l \cdot min^{-1}$. In practice, the resistance to breathing was also increased by the breathing valve (from manufacturer's manual).

Table 2. Pneumotachometer resistance to airflow. Signal and back pressures throughout the range 0-800 $l \cdot min^{-1}$ air (from manufacturer's manual).

Airflow ($l \cdot min^{-1}$)	**Signal pressure** (mmH_2O)	**Back pressure** (mmH_2O)
80	1.775	0.4
160	3.529	0.9
240	5.260	1.6
320	6.985	2.3
400	8.739	3.2
480	10.523	4.3
560	12.310	5.4
640	14.119	6.7
720	15.920	8.1
800	17.740	9.5

2.2.3.d. Pulmonary ventilation

Pulmonary ventilation is calculated by measuring *inhaled* flow rates on a breath-by-breath time-scale. The advantage of this arrangement is that the pneumotachometer (PMT) does not become contaminated with the moisture found in normal expired air.

2.2.3.e. Breathing valve

A two-way (T-shape) non-rebreathing valve (Hans Rudolf, Series 2700) is used to allow inhaled and exhaled air to flow through the analyser. A detailed description of this valve is given in Diagram 9. This arrangement results in some resistance to breathing, which is kept to a minimum due to the large diameter of the tubing connectors and the ability of the subjects to acclimatise to modified breathing within minutes. The differential pressures of the resistance to breathing have been assessed and the results are presented in Table 3.

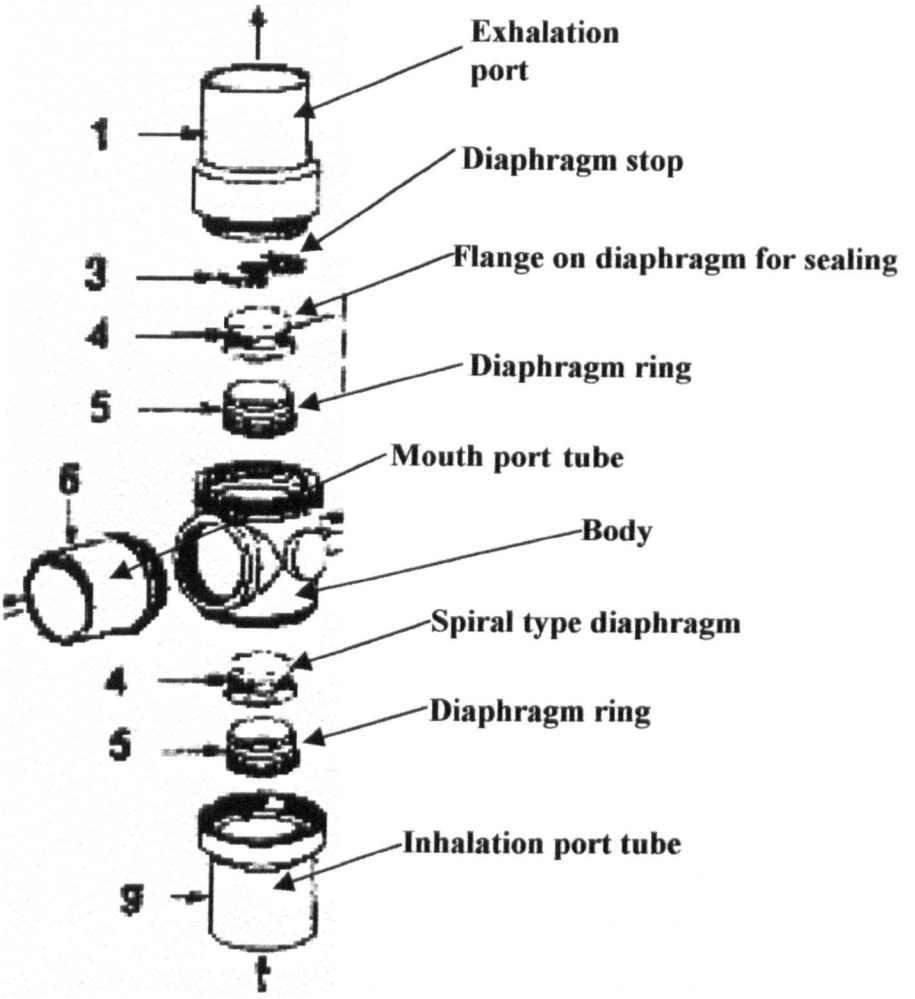


Diagram 9. The Hans Rudolf breathing valve used with the COVOX Microlab analyser, showing the different parts that connect the inhalation and exhalation ports (from manufacturer's manual).

Table 3. Differential pressures (cm H_2O) of the T-shape Hans Rudolf valve (Series 2700) used with the COVOX Microlab analyser.

Airflow ($l \cdot min^{-1}$)	Inspired Pressure (cm H_2O)	Expired Pressure (cm H_2O)
50	0.5	0.6
100	0.7	0.8
150	1.0	1.1
200	1.3	1.4
300	2.1	2.4
400	3.1	3.9
500	4.3	5.7
600	5.7	7.8
700	7.2	10.3

2.2.3.f. Calibration of the COVOX Microlab analyser

Calibration of the COVOX Microlab is performed using zero nitrogen (0% CO_2, 0% O_2) and span (4.98% CO_2, 21.72% O_2) calibration gases. Gas analyser 'zero calibration' is achieved by flushing the sampling system with nitrogen (supply pressure at 15 psi [pounds per square inch] = 1 bar) and then adjusting the front panel potentiometers so that the output signal reads 0 Volts. Gas analyser 'span calibration' involves a span gas purge of about 2 minutes with supply pressure at 15 psi. At the end of the span gas purge the O_2 and CO_2 analysers are automatically calibrated according to the pre-set gas values (i.e. 21.5% O_2 and 4.95% CO_2). These values are set by certified analysis of concentrations supplied with the calibration gas (BOC Gases Ltd., Guilford, Surrey, UK). The O_2 and the CO_2 concentration of the calibration gas was checked periodically by a laboratory technician using the Haldane method (Haldane and Graham, 1920). The O_2 and the CO_2 concentration in the

calibration gas obtained using the Haldane method was compared with the certified values supplied with the calibration gas. An average of ±1% coefficient of variation was reported. This obviated the need to use the Haldane method to check the O_2 and the CO_2 concentration in the calibration gas during the calibration procedure of the COVOX Microlab, given the fact that the Haldane method is a reliable, yet labour-intensive method.

To calibrate the pneumotachometer, a Hans Rudolf 3-litre calibration syringe (Plate 7) is connected to a breathing tube on the analyser and with each stroke a 3-litre volume of air is passed through the system. This procedure is repeated until the required accuracy between the cumulative volume of air and the number of strokes is achieved. For example, the cumulative volume of air for ten strokes must be between 29.9 and 30.1 litres (ten strokes x 3 litres). The gas analysers were calibrated before, during (every 30 minutes) and immediately after each test session to ensure accuracy of readings. A period calibration (every week) was also performed to maintain the on-line gas analysis system in good working order.

2.2.3.g. Analysis of expired air

To ensure accuracy of readings, the COVOX Microlab was calibrated immediately prior, during (every 30 minutes) and after each test session. During testing, expired gases were first directed through the triple-screen pneumotachometer. At this point, the airflow was converted into a proportional differential pressure. This pressure was converted into a voltage proportional to airflow through use of a manometer. The expired gases were then directed into a mixing chamber and were sampled every 15 seconds. It was possible to manipulate the sampling interval using this system (5, 10, 15, or 30 seconds). For the purposes of this reliability study, a 15-second sampling interval was used. The gas volumes were measured dry using the COVOX Microlab analyser, as expired gases were sampled through a column containing 'Drierite'

(anhydrous calcium sulphate). The granules of this chemical absorbed the moisture in the expired air. This was demonstrated by a change in the colour of the chemical (drierite turned from blue to pink when saturated with moisture). After this, oxygen uptake ($\dot{V}O_2$) was internally computed and the values were displayed on the computer screen. $\dot{V}O_2$ was then computed for every minute of collection as the average of four 15-second values.

2.2.4. The COSMED K2 analyser

A portable gas analyser (COSMED K2, Rome, Italy) was used to assess oxygen uptake during free swimming and dry-land exercise (see Chapter 5). The K2 is a telemetric system and comprises three separate parts: a) a portable unit carried by the subject (transmitter), b) a signal receiver unit, which processes data that are printed and archived and c) a battery charger unit (Plate 8). The analyser was calibrated prior to and immediately after each session of testing (see pages 68-69). This system can only sample oxygen uptake, as it is not equipped with a carbon dioxide analyser. Expired gases pass through the O_2 sensor, which detects the O_2 concentration in the expired air and logs the data in analogue values. The data are then transmitted to the receiver unit (equipped with an analogue-to-digital converter), which converts them to numerical values. It is possible using this equipment to manipulate the sampling interval for expired O_2 (5, 15, 30 seconds). For the purposes of the study in this thesis expired O_2 was sampled every 5 seconds and was averaged for every 30 seconds.

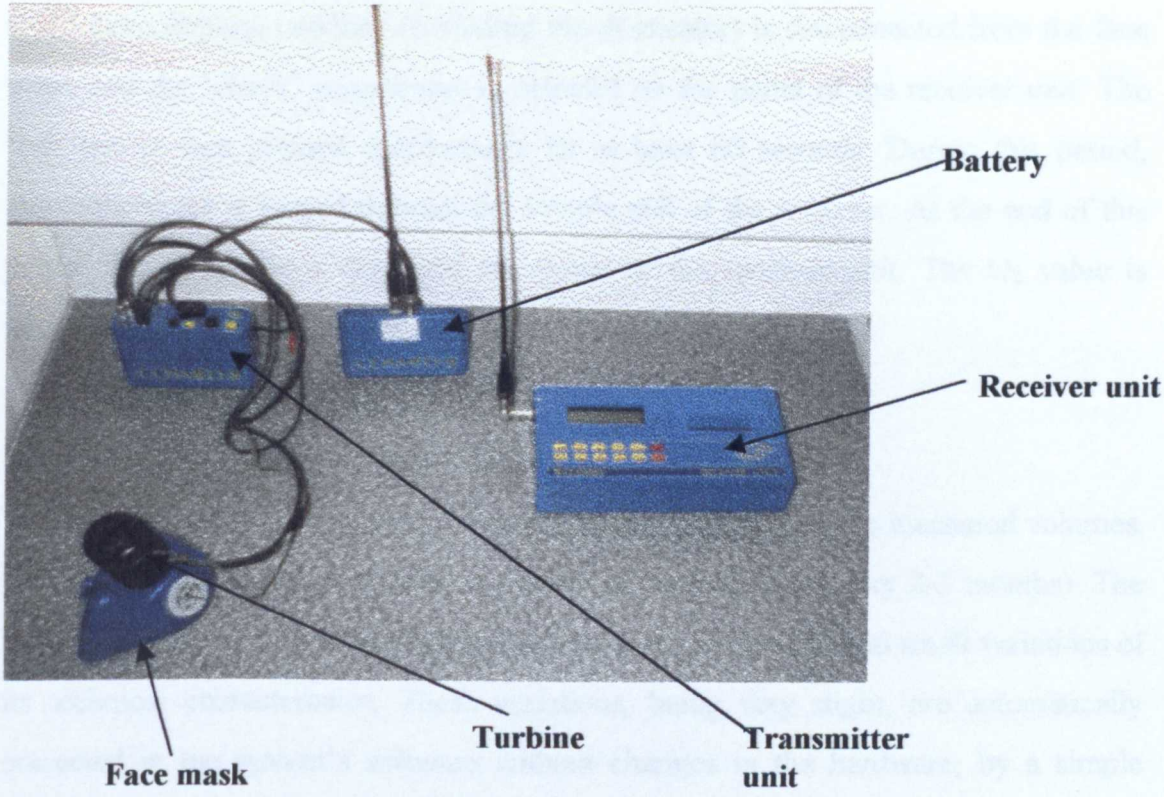


Plate 8. The COSMED K2 analyser showing the face mask and the transmitter, battery and receiver units.

2.2.4.a. Calibration of the COSMED K2 analyser

This apparatus (COSMED K2, Rome, Italy) requires two calibration procedures: one for the O_2 analyser and the other for the control and eventual setting of the 'turbine correction factor'.

2.2.4.b. Calibration of the O_2 analyser

Calibration of the O_2 analyser is performed prior to and immediately after each test. Factors such as, the partial pressure value of the air may vary in function according to atmospheric conditions and in particular to barometric pressure and thus, the calibration is carried out before each test. The procedure consists of flushing the mixing chamber with atmospheric air. This results in the activation of the sampling pump so that the % O_2 value coincides with the expected value (i.e. 20.9%). First, the

small gas-sampling capillary (including the dessicator) is disconnected from the face mask and the 'check' programme is selected on the panel of the receiver unit. The 'cal' key is then pressed continuously for at least 60 seconds. During this period, atmospheric air is passed through the sample cell of the analyser. At the end of this period, the % of O_2 is displayed on screen of the receiver unit. The O_2 value is adjusted to the expected calibration value using the O_2 gain knob.

2.2.4.c. Calibration of the turbine

The turbine calibration procedure consists mainly of verifying the measured volumes. Routine calibration of the turbine is performed periodically (every 2-3 months). The turbine (i.e. the mobile rotor of the measuring system) is subject to small variations of its technical characteristics. These variations, being very slight, are automatically corrected in the system's software without changes in the hardware, by a simple procedure for the calculation of a 'volume correction factor'. This indicates the percentage correction that the processor applies to the measured volume. The optimal condition is when the value of the correction factor is 100 (i.e. 0% correction); 101 is equivalent to a correction of measured volumes equal to +1%; 99 equivalent to –1% and so forth. The maximum advisable correction is between ± 20 %.

To calibrate the turbine, a Hans Rudolf 3-litre syringe (see plate 7) is used. The syringe is attached to the turbine and a number of inspirations/expirations (tidal volume) are carried out. This activity is continued until the minute ventilation is calculated twice. Then, the 'check' key is pressed and the measured volume is indicated on the display screen of the microprocessor and the syringe volume used (i.e. 3-litres) is inserted (COSMED K2, User's manual).

2.3. Blood Lactate Analysis Equipment

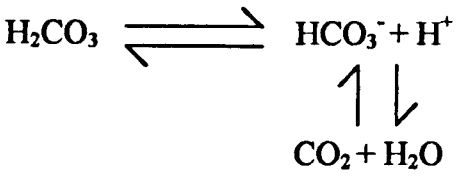
2.3.1. Principles of blood lactate measurement

Blood lactate is a metabolic intermediate that is produced by many tissues of the human body, but chief amongst these is skeletal muscle. Blood lactate concentration can rise sharply during exercise when the rate of glycolysis exceeds the mitochondrial removal of pyruvate (Juel and Pilegaard, 1999). During low and moderate intensity exercise, the ATP (adenosine triphosphate) for muscular contraction is made available predominantly through energy generated via oxidative phosphorylation (the oxidation of hydrogen ions; McArdle et al., 1991). This process is associated with the complete breakdown of glucose or glycogen during the processes of anaerobic glycolysis and the Kreb's cycle (Marieb, 1992). Any lactic acid formed by the energy metabolism in light or moderate exercise is rapidly oxidised and, as such, blood lactate levels remain fairly stable (McArdle et al., 1991).

Under conditions associated with high intensity exercise, large amounts of lactate can be formed and, when the rate of production is higher than the rate of release to the surroundings, lactate accumulates in the muscle fibres (Juel and Pilegaard, 1999). In particular, during high intensity exercise, the energy requirement becomes increasingly provided by anaerobic glycolysis, as the release of hydrogen ions (H^+) begins to exceed their oxidation through the respiratory chain (Katz and Sahlin, 1988). The excess H^+ produced during anaerobic glycolysis ($NADH + H^+$) combine with pyruvic acid which is catalysed by the enzyme *lactate dehydrogenase* to form lactic acid (Marieb, 1992) in the reversible reaction:

$$\text{Pyruvic acid} + NADH + H^+ \underset{\text{Dehydrogenase}}{\overset{\text{Lactate}}{\rightleftharpoons}} \text{Lactic acid} + NAD^+$$

This increase in H^+ concentration is referred to as acidosis (decrease in pH below 7.4). Metabolic acidosis is regulated through the activity of the bicarbonate buffer, which consists of carbonic acid (HCO_3^-) and sodium bicarbonate (H_2CO_3) (Southerland, 1990). H_2CO_3 exerts a strong buffering action on lactic acid and this causes the formation of sodium lactate and carbonic acid (Southerland, 1990). Any additional increase in H^+ brought about by HCO_3^- dissociation causes the dissociation reaction to move in the opposite direction with the ultimate formation of CO_2 and water (H_2O). An increase in CO_2 in the plasma stimulates the respiratory centre (hyperventilation) and CO_2 is expelled through the lungs (McArdle et al., 1991). Conversely, when the concentration of H^+ is reduced (alkalosis; increase in pH above 7.4) CO_2 is retained to combine with H_2O and the acidity is normalised (McArdle et al., 1996). The activity of the bicarbonate buffer is summarised in the following reaction:



As early as the 1920s, it was suggested that there is a link between blood lactate, respiratory gas exchange and fatigue (Hill and Lupton, 1920). Wasserman and McElroy (1964) observed that there is a critical work rate at which blood lactate concentration rises in an exponential fashion and termed this point 'anaerobic threshold' (AT) or 'ventilatory threshold' (VT; Fukuba et al., 1988). The term AT indicated the amount of work that can be performed by the aerobic metabolism. The increase in blood lactate concentration during exercise is thought to cause a non-linear increase in ventilation, as a result of the bicarbonate buffering of the excess H^+ of lactate in the blood and the subsequent production of CO_2 (Shimizu et al., 1991). However, there is controversy as to whether AT coincides with the sudden increase in blood lactate concentration during incremental exercise. Some studies have demonstrated that AT occurs concurrently with the lactate inflection point (Davis et

al., 1976; McLellan and Gas, 1989), whereas others have not (Hughes et al., 1982; Simon et al., 1986).

After the pH is regulated, the remaining lactate will either be metabolised in the muscle or be released from the fibre to the interstitial space. From the interstitium, lactate can be either taken up by neighbouring muscle fibres (process called the 'lactate shuttle') or it can enter into the blood and subsequently be taken up by other tissues (process called the 'Cori cycle') including resting and active muscle beds (Juel and Pilegaard, 1999).

During the *'lactate shuttle'*, a large proportion of lactate is actively oxidised in working muscle (Brooks, 1985). This includes the conversion of lactic acid back to pyruvic acid, which is then broken down to carbon dioxide (CO_2) and water (H_2O) in the mitohondria (Lamb, 1984). This may occur at a different site within the same muscle that initially produced the lactic acid (Brooks, 1985). For example, lactic acid produced by type IIb (Fast Glycolytic) fibres, diffuses or is transported into type I (Slow Oxidative) fibres of the same muscle. During exercise, the 'lactate shuttle' can provide significant amounts of fuel (Brooks and Gaesser, 1980). Alternatively, lactate can also diffuse out of the muscles into the blood stream and be taken up and degraded for energy by other tissues (Lamb, 1984). The fraction that will be released to the blood will depend on the actual conditions, of which muscle blood flow and muscle mass involved in the exercise are important factors (Juel and Pilegaard, 1999). However, much of the lactate produced within a working muscle is consumed within the same tissue and never reaches the venous blood (Brooks, 1985).

During the *'Cori cycle'*, some of the lactate produced in the muscle diffuses out of the cells and is transported to the liver where it is converted back to glucose-6-phosphate (gluconeogenesis) and is stored as glycogen (Marieb, 1992). The liver glycogen can then be broken down to glucose that enters the blood stream and is transported back to the muscles for use in glycolysis or glycogen storage (Lamb, 1984). The 'Cori

cycle' has implications for prolonged exercise and recovery as it helps to remove lactate and also replenishes blood glucose for continued energy supply to the muscles (Lamb, 1984).

During high intensity exercise, blood lactate begins to accumulate and rise in an exponential fashion (as a function of exercise intensity) at about 55% of the healthy, untrained subject's maximal capacity for aerobic metabolism (Costill et al., 1973; Davis et al., 1979. In endurance-trained individuals, the threshold for lactate build up (onset of blood lactate accumulation [OBLA]) occurs at a higher percentage (80-90%) of the athlete's maximum capacity for aerobic metabolism (Conley et al., 1981; Wasserman et al., 1991; Wasserman et al., 1992). The measurement of OBLA can serve as a predictor in determination of the maximum workload that can be performed by the oxidative metabolism (Wasserman and McIllroy, 1964). Therefore, the measurement of blood lactate is a 'key' concept in the evaluation of dry-land ergometry in physiological assessment of swimmers.

2.3.2. The Fluorimeter

A single-sided Fluorimeter (Plate 9; Locarte LF 8-9, Locarte Scientific Instruments, London, UK) was used as the criterion method with which the YSI blood lactate analyser (presented in the following section) was compared to ensure validity of blood lactate concentration measurements. It has been previously shown that the Fluorimeter is a simple, rapid and reliable method for the determination of blood chemistry measures such as glucose, lactate, pyruvate, alanine, 3-hydroxybutyrate and acetoacetate (Maughan, 1982). The reliability of the Fluorimeter was also examined (see Reliability of Blood Lactate Analysis methods section).

According to the manufacturers, the Locarte Fluorimeter provides an exceedingly sensitive means of measuring fluorecence in liquids of semi-transparent substances such as filter paper and in special cases, of non-transparent substances. Excitation wavelength (from 235 mu onwards) may be selected by glass or liquid filters. The

latter applies especially in the short ultra-violet wave. For the purposes of the reliability and validity studies in this thesis Pyrex glass (75 x 10 mm) tubes were used as cuvettes. A corning filter (no. 5860) is used to isolate the excitation beam: the emitted light is isolated by combination filters (no. 4303 and no. 3387). In addition to these a gelatine filter is used in the emission path placed on the sample side of the other two filters. The equipment consists of two main sub-units, namely an ancillary lamp power supply sub-unit and the Fluorimeter sub-unit. The ancillary lamp power supply sub-unit consists essentially of a constant *voltage transformer* and a *ballast resistor network.* These items are housed in a metal case, the top of which incorporates ventilation holes to allow heat dissipation by natural convection. The ancillary lamp housing is attached to the side at the front of the main casing. The housing is designed so that the arc lamp in use is effectively cooled, thereby ensuring that there is no rise in temperature in the optical block or cuvette holder when the lamp is energised. The Fluorimeter sub-unit consists of a lidded case machined from a solid aluminium casting. The case houses *an optical block, a photo-multiplier, an electronic sub-assembly plate, a digital voltmeter* and *a monochromator* (single colour). The *optical block* is machined from a solid casting and houses a lens system, a filter compartment, a cuvette holder and an iris diaphragm. The *photomultiplier,* which is fitted to the back of the optical block, is housed in a tufnol tube that also houses a dinode resistor chain. The *electronic sub-assembly plate* is housed to the rear of the optical block. An E.H.T. transformer incorporated in the assembly is fed with the appropriate power supply from the constant voltage transformer in the ancillary lamp power supply sub-unit. The *digital voltmeter* presents results as an illuminated digital display on the front panel. Full scale reading is ± 1.999 and three ranges are available (0.1, 1 and 10) increasing the sensitivity of the instrument three-fold. With the digital voltmeter an output for a recorder is directly available from the coaxial socket on the front panel of the Fluorimeter on any of the three ranges such that a display reading of 1000 will give 1 volt at 5 mA. The *monochromator* is positioned between the photomultiplier and the secondary filter compartment of the

optical block. Stable light sources are derived from arc lamps (250 nm - 700 nm) having Mercury (Hg), Zinc (Zn), Thalium (Tl), and Cadmium (Cd).

The operation of the instrument is performed through use of controls, which are located on the front panel of the Fluorimeter sub-unit. The 'DVM Range' switch is a rotary switch marked 0.1, 1, 10.With the switch set to '1' range, full-scale reading will be indicated for a signal of 1 uA (the '10' and '0.1' ranges are expected to give 10 uA and 0.1 uA, respectively). The 'Coarse Sensitivity' and 'Fine Sensitivity' controls are used to stabilise a fluctuating digit of a signal (usually the 4^{th} digit) by setting them to a low setting. To compensate for the low setting, the 'Iris Diaphragm' is opened to admit more light. The 'Iris Diaphragm' control is used to govern the volume of light reaching the sample in the cuvette. The 'Zero Supression' switch is a rotary switch that enables the recorder span to be set at a desired reading without changing the sensitivity of the instrument. This arrangement allows a reagent blank to be adjusted to zero . The main advantage of this switch is that on setting up an estimation it is possible to set a top standard to read 1.000 on the digital voltmeter and the blank to read zero, thus enabling the readings to be taken as a direct percentage of the standard.

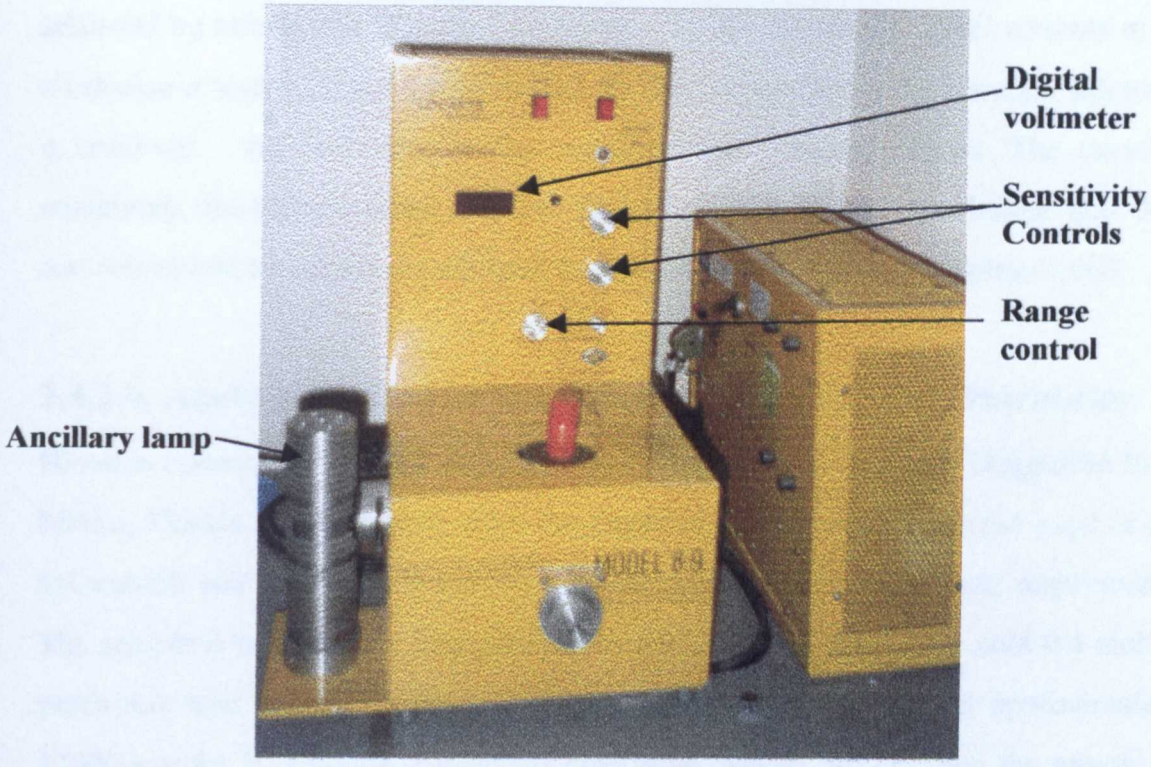


Plate 9. The Locarte Fluorimeter showing the ancillary lamp, the digital voltmeter display unit and the range and sensitivity controls.

2.3.2.a. Calibration of the Locarte Fluorimeter

A reagent blank and a top standard is prepared. The Pyrex glass tube (cuvette) is filled with the top standard approximately three quarters full. To ensure that these tubes are scrupulously clean, they are boilled in alkali and nitric acid and are washed in distilled water (Lowry and Passonneau, 1972) prior to use. The 'Sensitivity Coarse' and the 'Sensitivity Fine' switches are rotated in a clockwise direction to the 12 o'clock position. The 'Range' control is set to the full position. The 'Iris Diaphragm' control is set to half-open position and the digital voltmeter is set to the '1' range. The cuvette is inserted in the cuvette holder and the holder cover is closed. The digital voltmeter must now indicate approximately 1.000 (the 'Iris Diaphragm' is opened further if the value is lower). In the case that the digital voltmeter fails to indicate full-scale deflection, the 'Iris Diaphragm' is adjusted to the half-closed position and the photomultiplier sensitivity is increased. This is

achieved by turning the 'Sensitivity Coarse' and the 'Sensitivity Fine' controls in a clockwise direction. Once the calibration of the Fluorimeter to the standard solution is achieved , the calibration to the reagent blank solution follows. The cuvette containing the reagent blank is filled and inserted in the cuvette holder and the controls mentioned above are adjusted so that the digital voltmeter displays 1.000.

2.3.2.b. Analysis of blood lactate concentration using the Fluorimeter

Blood is collected into 20-µl disposable glass capillary tubes (Dade Diagnostic Inc., Miami, Florida, USA) directly from the finger of the subject's preferred hand or an antecubital vein using the finger prick or the venepuncture procedure, respectively. The sample is immediately deproteinised by addition to 200-µl of ice cold 0.4 $mol \cdot l^{-1}$ perchloric acid and the precipitate is separated by centrifugation at approximately 12000 x g for 30 seconds (Eppendorf centrifuge, Model 5412). Then the sample is frozen until it is analysed.

All enzymes, cofactors and buffers used in the analysis of lactate and or preparation of the instrument are supplied by Boeringer (Boeringer, London, UK). Solutions of NAD^+ are freshly prepared every fortnight. A 5 $mmol \cdot l^{-1}$ solution is prepared by dissolving 3.3 mg of free acid in 1 ml of distilled water. Enzymes and cofactors in solution are stored at 4 °C. Lactate is measured on a 20-µl of supernatant. The analysis depends on the inter-conversion of metabolites linked to a change in the oxidation state of NAD^+. The metabolite to be measured is linked by the following reaction:

$$\text{L-lactate} + NAD^+ \xrightleftharpoons{\text{LDH}} \text{Pyruvate} + NADH + H^+$$

The assay conditions for measuring lactate use particular concentrations of a buffer, a cofactor and an enzyme. The buffer used is hydrazine of 1.1 $mol \cdot l^{-1}$ and pH of 9.0. A solution of 5 $mmol \cdot l^{-1}$ NAD is used as cofactor, whereas the enzyme used is lactate

dehydrogenase (LDH; EC: 1.1.1.27, 2.570 U·ml^{-1}). The reaction mixture consists of 1 ml buffer, 50 µl NAD and 10 µl LDH. For a sample volume of 20 µl the standards used are 0, 100, 200 and 300. For those cases in which the levels of lactate are markedly elevated above the normal range, as in the measurement of post-exercise lactate, the range of these assays is extended by using higher standards and by increasing the cofactor concentrations proportionately (0.033 g NAD in 10 ml distilled water; standard dilution 1:200). Also, in the case of very low lactate levels, as in the measurement of resting lactate levels, lower standards and proportionate cofactor concentrations are used (0.033 g NAD*4 in 2.5 ml distilled water; standard dilution 1:100). The incubation time is 30 minutes for samples whose readings are expected to take values below 7.5 mmol·l^{-1}, whereas the incubation time for samples whose readings are expected to take values above 7.5 mmol·l^{-1} the incubation time is 1 hour.

At the end of the incubation period the sample is diluted by addition of 1 ml of bicarbonate buffer (20 mmol·l^{-1}, pH: 10). The fluorecence is then read; for lactate the blank fluorecence is set to zero. Sample values are obtained by comparison of readings with the standard curve (see Figure 1). The fluorimetric analysis of lactate as described above (Maughan, 1982) is based on another method described by Olsen (1971). By conducting these measurements in a small volume (20-µl) with subsequent dilution favourable reaction kinetics can be achieved, while this procedure produces markedly lower blanks by enabling the final concentration of a cofactor, enzyme and other fluorescent substances to be kept to a minimum (Maughan, 1982).

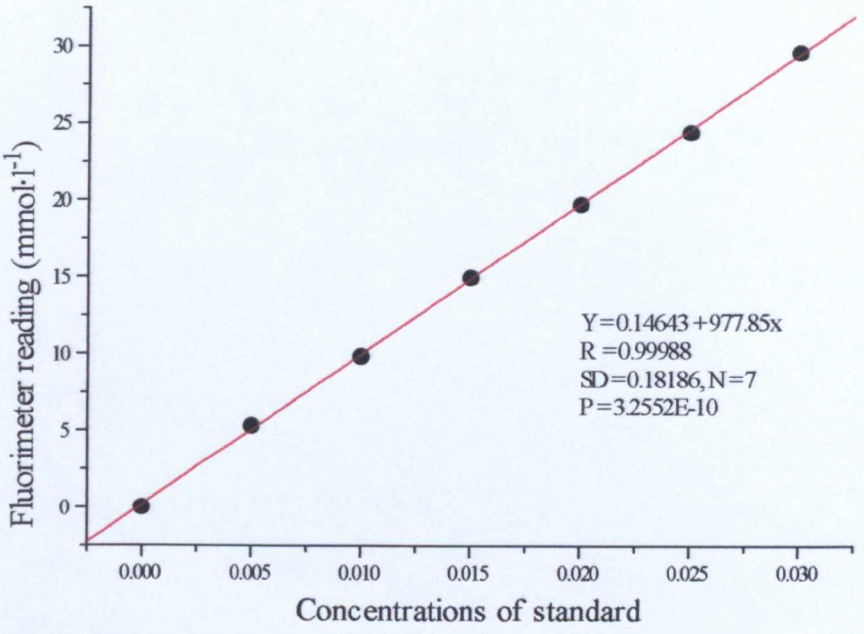


Figure 1. The Fluorimeter standard curve.

2.3.3. The YSI Lactate Analyser

A YSI Model 2300 STAT PLUS Glucose and Lactate Analyser (Yellow Springs Instrument Co., Inc., Yellow Springs, Ohio, USA; Plate 10) was used for the purposes of blood lactate analysis in one of the studies in this thesis (see Chapter 3). This is a laboratory instrument intended for use in clinical care and sports science applications. It provides rapid measurements of glucose in whole blood, plasma or serum; and of L-lactate in whole blood, plasma or cerebrospinal fluid (CSF).

The standard features of this instrument include microprocessor control, menu-driven set up with battery backed-up memory, built-in data printer and complete diagnostic software. Calibration procedures are automatic and programmable and there are three selectable concentration units ($mmol \cdot l^{-1}$, $mg \cdot dl^{-1}$ or $mg \cdot l^{-1}$) in which glucose or lactate

can be measured (YSI User's manual). For the purpose of the study presented in this thesis (see Chapter 3), the YSI analyser was only used for lactate measurements.

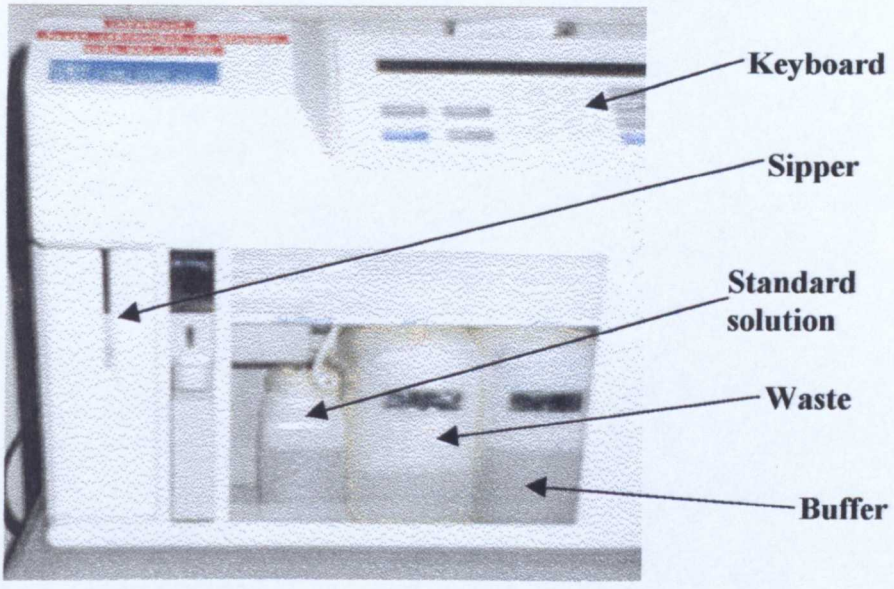


Plate 10. The YSI analyser, showing the standard and buffer solutions and sipper.

2.3.3.a. Calibration of the YSI analyser

Calibration of the YSI 2300 STAT PLUS analyser was performed using glucose and lactate concentration standards (1.8 $g \cdot l^{-1}$ and 0.45 $g \cdot l^{-1}$, respectively) and established the sensors' response, in nanoamps (nA) of current, to a known concentration of substrate. A sensor consists of an electrode and an enzyme membrane. Under optimal conditions the sensor's response depends on diffusion limitation of the substrate. When the substrate diffuses at a greater rate than the enzyme can turn over, product enzyme kinetics define the response and non-linearity as a symptom. This occurrs when an enzyme membrane ages. The sensitivity of the sensors varies with temperature changes. The temperature probe in the sample chamber monitors the fluid temperature very near to the enzyme sensor. The sample results were corrected for the difference in temperature between the sample and the calibration.

To maintain a sample ready status (above 5 nA), the 2300 Stat Plus self-calibrates every five samples or every fifteen minutes. Alternatively, default calibration parameters can be altered to loosen or tighten calibration specifications. The instrument re-establishes a calibration reference point after every calibration. If a difference of more than 2% between the current and the previous net calibration or after a sample chamber temperature drift of more than 1 °C occurrs, the instrument automatically repeats calibration. The sensor's net current for calibration is displayed and printed.

The 2300 Stat Plus employs a capacity level sensing on the sipper and in the calibrator, waste and supply bottles. The sipper sensor detects the sample surface at the Test Tube Sample Station and then travells into the sample about 3 mm. This controlled immersion depth permitts the use of sample tubes that are filled to different heights without significant carry-over between samples. As an extra safety precaution, if the sipper detects contact with conductive bodies (i.e. a hand), it immediately stops, waits for several seconds and then returns to the sample chamber (YSI User's manual, p. 5-5).

2.3.3.b. Analysis of blood lactate using the YSI method

For resting blood samples, the subject immerses his/her non-preferred hand into lukewarm water for approximately five minutes. This technique is used to facilitate blood flow to the finger capillaries. Then the subject is seated on a chair and his/her hand is dried using a paper towel. The middle or index finger is selected and swabbed with a 70% alcohol solution using cotton wool. A prick is made on the tip of the finger using Autolet (Owen Mumford Ltd., Oxford, UK). The first drop of blood is swabbed away, as some blood cells may have been damaged due to the pricking. The blood sample is collected into a microhaematocrit tube and then run gently into a 500-ul size micro Eppendorf tube (Richardsons of Leicester, Leicester, UK). The Eppendorf tube is inserted at the port of the YSI analyser and the command 'SAMPLE' is keyed in at the analyser's keyboard. This command directs

the sipper into the sample, where a further sample is taken and introduced into the analyser. The result for blood lactate concentration is given on screen within one minute from sampling.

2.4. Measurement of Heart Rate

2.4.1. Principles of heart rate measurement

Heart rate (HR) is a physiological function that can be used to quantify exercise stress. It has been well documented that heart rate increases in linear fashion with increasing intensity of exercise and also, when heart rate reaches its maximal value the exercising individual is considered to be very close to exhaustion (McArdle et al., 1996). For each person, heart rate and oxygen consumption tend to be linearly related (as a function exercise intensity) throughout a large portion of the aerobic work range. If this precise relationship is known, heart rate can be used to estimate oxygen uptake indirectly (and then calculate energy expenditure). Even though this may be of limited use for research purposes, it is a practical technique for estimating energy expenditure when oxygen uptake cannot be measured during the activity (McArdle et al., 1991). Also, it has been documented that there is an inverse linear relationship between maximal heart rate and advancing age (Åstrand and Rodahl, 1986) however, longitudinal studies have shown a wide individual variation in the decline in maximal heart rate with age (Hollmann and Hettinger, 1980). In addition, it has been shown that heart rate at a given oxygen uptake is higher when exercise is performed with the arms than with the legs (Vokac et al., 1975). Conversely, the maximal heart rate responses to arm exercise are lower (by approximately 10 $b \cdot min^{-1}$) than respective responses to leg exercise (Magel et al., 1975). These findings have implications for those sporting activities that engage the upper and/or lower body muscle mass. Furthermore, it has been noted that heart rate at a standard work rate decreases gradually as the training progresses (Åstrand and Rodahl, 1986). It has been suggested that improvements in aerobic capacity occur if exercise is of sufficient intensity to increase heart rate to about 70% of maximum (50-55% $\dot{V}O_{2max}$; McArdle

et al., 1991). Heart rate can be influenced by a variety of factors. These may include environmental factors, such as exercise in the heat and also emotional factors, nervousness, apprehension, stress and anticipation of exercise (Åstrand and Saltin, 1961). Therefore, the measurement of heart rate is another important physiological variable that needs to be examined in the evaluation of dry-land ergometry in physiological assessment of swimmers.

2.4.2. Heart rate instrumentation

Heart rate (HR) was recorded continuously throughout the tests using a radio-telemetered chest strap electrode and a micro-computer wrist receiver (Vantage, Polar Electro, Kempele, Finland). The micro-computer was set to record heart rate every 5 seconds during the tests. These data were stored in the memory of the micro-computer and they were later downloaded into an IBM compatible computer. During this procedure, a graphic representation of heart rate activity during the tests and the raw data were obtained. To allow measurements of heart rate during swimming in the swimming pool, a waterproof heart rate monitor (Polar Vantage, Polar Electro, Finland) was used and the same recording intervals were set. The data were stored in the archive of the receiver unit and were later downloaded into an IBM compatible computer using the same specially designed software, as described previously. All the above procedures were performed by the investigator.

2.5. Assessing Reliability of Measurement Tools

2.5.1. Introduction

Reliability can be defined as the 'consistency of measurements', 'consistency of an individual's performance on a test' or 'the absence of measurement error' (Safrit and Wood, 1989). Atkinson and Nevill (1998) have quoted a variety of terms in relation to reliability, such as *'repeatability'*, *'reproducibility'*, *'consistency'*, *'agreement'*, *'concordance'* and *'stability'*. They have also stated that 'there is always an element of error in continuous measurements and therefore, reliability can be considered as the amount of measurement error that has been deemed acceptable for the effective practical use of a measurement tool'. The same workers have suggested that it is reliability that should be assessed initially, in a new measurement tool, since such a tool will not be considered to be valid (i.e. reflecting what it is designed to measure), if the measures it produces are not consistent.

Reliability is relevant to the study of method comparison, as the reliabilities of two methods of measurement limit the amount of agreement that is possible (Bland and Altman, 1986). If one method has poor reliability (i.e. there is considerable variation in repeated measurements on one subject), the agreement between methods is bound to be poor too. When the established method is the more variable one, even a new method which is 'perfect' will not agree with it, whereas if both methods have poor reliability, the problem is further exacerbated (Bland and Altman, 1986).

There are two components of variability associated with each assessment of measurement error. These are *random error* and *systematic bias* (Chatburn, 1996). The first component of variability between repeated tests is the degree of random error. Large amounts of random error could arise from inherent biological or mechanical variation, or inconsistencies in the measurement protocol (Claudwells et al., 1994). The second component, the systematic bias, refers to a general trend for measurements to be different in a particular direction (either positive or negative)

between repeated measurements. This can be determined i.e. if there is any statistically significant bias between the tests, by comparing the means of a test and re-test using a paired t-test and also through calculating the Coefficient of Variation (CV%). Therefore, the random error and systematic bias need to be closely examined when the reliability of a new measurement tool is being assessed.

Another issue in the assessment of reliability is how the measurement error relates to the magnitude of the measured variable. For example, if the amount of measurement error increases with increasing measurement values, then the data are called *'heteroscedastic'*. These data also show departures from a normal distribution (i.e. positive skeweness). When there is no relation between the error and the size of the measured variable, the data are described as *'homoscedastic'* (Atkinson and Nevill, 1998). Heteroscedasticity or homoscedasticity should also be examined in reliability studies.

'Method reliability' is, therefore, an issue of paramount importance in the process of assessing agreement between two methods of clinical measurement. Indeed, it has been suggested that method reliability is examined first before assessing agreement between two different methods of measurement and for all methods involved (Nevill and Atkinson, 1997). The aim of the present investigation was to assess the reliability of the different equipment that was used in measurements of gas exchange and blood chemistry variables in the studies presented in this thesis, namely the COVOX Microlab and COSMED K2 on-line gas analysis systems and the YSI 2300 blood lactate analyser.

2.5.2. General procedure

The procedure used to assess reliability of measurement tools in this thesis was adopted from Bland and Altman (1986) and also from Nevill and Atkinson (1997). The reliability of the COVOX Microlab and COSMED K2 gas analysis equipment was examined using two well-established techniques. These techniques are referred to as 'limits of agreement' (LOA) and test re-test 'coefficient of variation' (CV%) in a set of repeated measurements (Atkinson and Nevill, 1998). The use of 'limits of agreement' in assessment of method reliability has been advocated (Bland and Altman, 1986); however, this technique is still in its infancy. A more widely known technique, such as the CV% was selected to supplement the findings of the limits of agreement. Also, the CV% was used as an alternative technique wherever the assessment of method reliability using the limits of agreement was likely to be affected by external factors. For example, the assessment of reliability of the COVOX Microlab analyser in measuring submaximal and maximal oxygen uptake responses to exercise is likely to be affected by intra-individual variation. One way to circumvent this problem would be to test the same subject on a number of occasions. However, then one would have to account for learning effects. Therefore, the use of 'limits of agreement' in this instance to calculate reliability would not be appropriate and consequently, would demonstrate poor method reliability. Therefore, the reliability of the above measurement tools for measuring submaximal and maximal oxygen uptake values was assessed using only the test re-test CV%.

2.5.3. 'Limits of agreement' and additive error

The first step in the calculation of 'limits of agreement' (LOA) is to calculate the differences between the first and the second measurement and their individual means. At this stage, the nature of the measurement error is examined. There are two types of measurement error; *additive* and *multiplicative* (Mullineaux et al., 1999). When the measurement error is additive, the data are called homoscedastic (the differences are not related to the mean), whereas a multiplicative measurement error is synonymous

with heteroscedasticity (the differences depend on the magnitude of the mean). To examine whether the measurement error is additive or multiplicative, the differences are ranked and plotted against their individual means. The correlation between the ranked differences and their mean is examined. If there is no correlation (either positive or negative) between the two variables (the differences do not depend on the magnitude of the mean), is acceptable to calculate immediately the LOA on the same data. The systematic bias is determined by a paired t-test. This test determines whether there is any significant difference between the data (Test 1 versus Test 2). The random error is determined by calculating the standard deviation (SD) of the differences and multiplying this value by 1.96 to obtain the 95% limits of agreement, as suggested by Nevill and Atkinson (1997). The best way to express LOA is as bias ± random error. Expressed this way, the LOA values are actually a measure of total error and it is more informative (Atkinson and Nevill, 1998) if the bias and random error are cited separately (-1.5 ± 12.9 $ml \cdot kg^{-1} \cdot min^{-1}$). The LOA can be displayed on a plot between the differences and their individual means (Bland and Altman plot). Alternatively, if the measurement error is multiplicative, the data require some sort of transformation before calculating the LOA. This procedure is described in the following section.

2.5.4. 'Limits of agreement' and multiplicative error

In the case of multiplicative error (e.g. an r-value of 0.15 denotes slight heteroscedasticity), the data require logarithmic (natural) transformation to reduce the correlation between the variables (Atkinson and Nevill, 1997). It has been suggested that in 'sports science' the majority of measurement errors are multiplicative (Mullineaux et al., 1999). Once the correlation has been reduced, the LOA can be calculated. The systematic bias and random error are determined as for homoscedastic data with the only difference that the logarithmically transformed data are used. The LOA can be displayed on a Bland and Altman plot of the logarithmically transformed differences against their logarithmically transformed individual means. The final step is to antilog the values for *systematic bias* and *random error* to show the total error of

measurement on a ratio scale. A high reliability coefficient is achieved, when 95% of the differences are no more than ± two standard deviations. This reliability standard has been suggested by the British Standards Institution (Bland and Altman, 1986).

On the other hand, however, if the correlation between the absolute differences and their means is negative, a different type of transformation may be required. Tabachnick and Fidell (1996) suggested a number of different types of data transformation. These transformations are applied to produce normality (data are normally distributed) and thus, they depend on the shape of the original distributions. Once the data are treated for normality, the LOA can be calculated as described previously. An example of the distribution of the data when the measurement error is additive and multiplicative has been provided in Mullinaeux et al. (1999).

2.6. Assessing Reliability of Gas Analysis Methods

Oxygen uptake ($\dot{V}O_2$) was the primary gas exchange variable that was investigated in all the studies presented in this thesis. The COVOX Microlab and the COSMED K2 gas analysis equipment were used to assess $\dot{V}O_2$. To ascertain the measurement error involved in the use of these two methods, the following reliability studies were undertaken. The reliability of the COVOX Microlab and the COSMED K2 system was assessed for resting, submaximal and maximal oxygen uptake values. In a subsequent section, these two methods were assessed for agreement with an accepted method of gas analysis, i.e. the Douglas bags method. Nevill and Atkinson (1997) have postulated that a method that has not been assessed for its reliability cannot be used for comparisons with other methods. It has also been suggested that the Douglas bags method is a well-established highly reliable method that can be used in assessment of gas exchange variables and especially $\dot{V}O_2$ (McArdle et al., 1996). However, the reliability of the Douglas bags method needs to be examined before it is used as a 'gold standard' in assessing agreement. Therefore, the following section

will include the procedures for assessment of reliability of the Douglas bags, the COVOX Microlab and the COSMED K2 gas analysis methods.

2.6.1. Reliability of the Douglas bags method

2.6.1.a. Resting measurements

The reliability of the Douglas bags method in measuring resting oxygen uptake values was examined using repeated measurements on one subject. The participant was instructed to abstain from food and vigorous exercise for at least two hours prior to the experiment. Laboratory conditions were controlled and monitored throughout the experiment. Seven Douglas bags were evacuated prior to testing. Also, the O_2 and CO_2 analysers used in the analysis of the expired air in the Douglas bags were calibrated (see pages 55-57). The subject was fitted with a mouthpiece connected to a Douglas bag and a nose clip and was asked to lie down (supine) on a bench. Then the subject was asked to breathe normally through the apparatus for a period of two minutes to accustomise to breathing though a resistance valve. The Douglas bag during this period remained closed. The valve on the Douglas bag was then opened at the end of an expiration and expired air was collected for a period of five minutes (measured with a stopwatch) in sequence with the pulmonary cycles (begin and end collection at the end of an expiration). The valve on the Douglas bag was then closed, the bag was removed from the expiratory hose and was taken for analysis (see page 57). An empty Douglas bag was connected to the expiratory hose and a second collection period of five minutes commenced. The same procedure was repeated until expired air had been collected into seven Douglas bags. Oxygen uptake ($\dot{V}O_2$) was calculated per minute of each collection period and seven values were computed each corresponding to one Douglas bag. The subject repeated this test 24 hours later under the same laboratory conditions.

2.6.1.b. Submaximal exercise test

Three subjects performed a submaximal 9-minute running exercise test on two occasions 48 hours apart. The test was performed on a motorised treadmill (Powerjog, MX 2000). The subjects performed a free warm-up at a self-selected pace prior to the test. The intensity of exercise was then set at 9.7 $km \cdot h^{-1}$ (2.7 $m \cdot s^{-1}$) and remained constant throughout the 9-minute period. The first three minutes of the running test were used to allow the subjects to reach steady-state conditions (where O_2 demand equals O_2 supply). Before this period elapsed, the subject was fitted with a mouthpiece and nose clip connected to a purpose-built bag rack carrying Douglas bags. This bag rack (De Montfort University Bedford, Bedford, UK; Plate 11) was designed to allow continuous collection of expired gases into Douglas bags and also measure the collection time in each bag through use of a computer program (De Montfort University Bedford, Bedford, UK). Six Douglas bags were attached onto the expiratory ports of the bag rack to allow continuous collection of expirate throughout the running test. A one-minute sample was collected into each one of the six Douglas bags. The subjects were allowed to breathe through the apparatus for 30 seconds to accustomise to breathing through a mouthpiece and also flush the connecting tubes with expired air. Expired air was then collected continuously for six minutes under steady state conditions and was immediately analysed for its O_2 and CO_2 content. The oxygen uptake values were computed for every minute of the collection period using the procedure outlined on page 57 of this chapter.

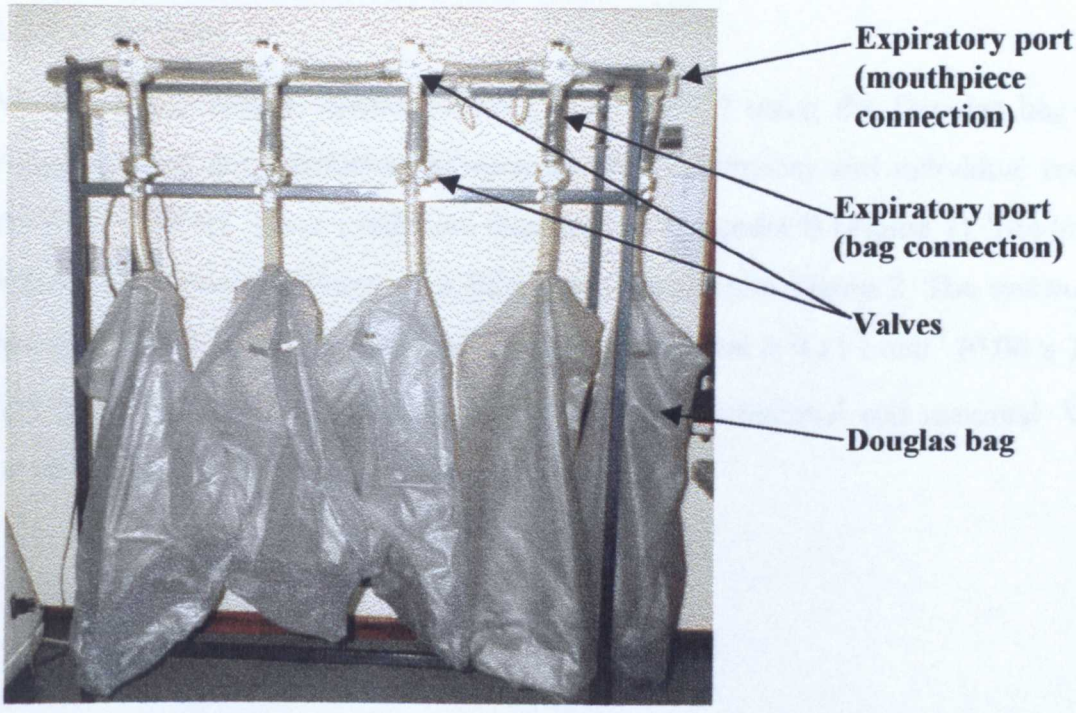


Plate 11. The bag rack (De Montfort University, Bedford, UK) used to allow continuous collection of expired air into Douglas bags, showing the expiratory port and the arrangement of the Douglas bags.

2.6.1.c. Maximal exercise test

To assess the reliability of the Douglas bags in measuring maximal oxygen uptake, three subjects performed a 9-minute running exercise test on two occasions four days apart. The subjects were given a warm-up period at a self-selected speed. The intensity of exercise was then set at 12.9 $km \cdot h^{-1}$ (3.58 $m \cdot s^{-1}$) and remained constant throughout the running test. The same procedure for collection and analysis of expired air was followed for the maximal as for the submaximal running test described above.

2.6.1.d. Results

For the resting oxygen uptake values ($\dot{V}O_2$; $l \cdot min^{-1}$) using the Douglas bag gas analysis system the correlation between absolute differences and individual means was r= 0.01 (P=1). These results are displayed in Appendix B (Figure 1). The limits of agreement were calculated on a Bland and Altman plot Figure 2. The systematic bias was –0.002 $l \cdot min^{-1}$ and the random error component ± 0.11 $l \cdot min^{-1}$ (0.06 x 1.96 SD). The coefficients of variation for the resting, submaximal and maximal $\dot{V}O_2$ values were 0.4%, 4.0% and 1.0% respectively.

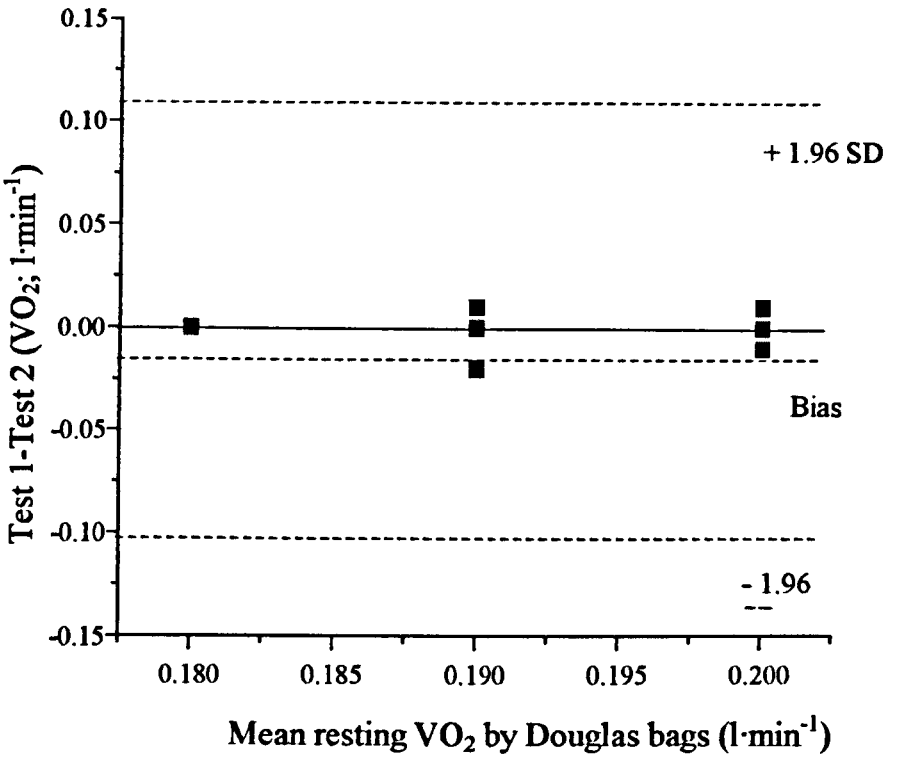


Figure 2. A Bland and Altman plot for the resting oxygen uptake ($\dot{V}O_2$; l·min^{-1}) measured by the Douglas bags gas analysis method. The bias line (-0.002) and random error lines (± 0.11) form the 95% limits of agreement.

2.6.1.e. Discussion

The findings of this study demonstrated that the Douglas bag method is, indeed, a highly reliable method for measuring resting, submaximal and maximal oxygen uptake ($\dot{V}O_2$) as stated by McArdle et al. (1996). There have not been any studies with which to compare the data from the study presented in this thesis. This is especially the case for the reliability of the resting $\dot{V}O_2$ values using the Douglas bags method, which in this study has been assessed using the 'limits of agreement' (LOA). A possible explanation for this is that the assessment of reliability of measurement tools using the LOA is a new technique and, therefore, not widely used in this context in the past.

Alternatively, there have been studies that have advocated the use of Pearson's correlation coefficient (r) in assessment of reliability of a measurement tool (Perrin, 1993; Coolican, 1994). Nevertheless, the use of the correlation coefficient in assessment of reliability has been deemed inappropriate (Sale, 1991). The main reason for the inappropriateness of the correlation coefficient to assess reliability is that the r-value does not provide any information on the magnitude of the measurement error. On the other hand, the LOA allow for calculations of the systematic bias and the random error of measurement, thus giving a global view of the variability profile of a measurement tool.

2.6.2. Reliability of COVOX Microlab

The reliability of the COVOX Microlab gas analysis method was assessed using the same procedure as described in the assessment of reliability of the Douglas bags method. The reliability of this measurement tool was assessed for resting, submaximal and maximal values of oxygen uptake. It was possible to calculate the 'limits of agreement' for the resting oxygen uptake values, but the reliability of the submaximal and maximal oxygen uptake values was examined using the test re-test coefficient of variation (CV%). The different tests that were used for collection of oxygen uptake data under these three conditions are outlined in the following section.

2.6.2.a. Resting measurements

To assess the reliability of the COVOX Microlab readings for resting oxygen uptake ($\dot{V}O_2$) values, expired gases were continuously collected from one individual, whilst resting (lying down supine) for a period of 8 minutes. To eliminate factors that might influence the $\dot{V}O_2$ readings, the subject abstained from vigorous exercise and intake of food for at least two hours prior to testing. Environmental temperature in the laboratory was set two hours prior to testing and kept constant at 20 °C throughout the period of testing. Barometric pressure was also recorded and the gas analyser was adjusted for any changes during calibration. The COVOX Microlab analyser was calibrated prior to and immediately after testing. The subject was fitted with a T-shape non-rebreathing mouthpiece (Hans Rudolf, Series 2700) connected to on-line gas analysis equipment (COVOX Microlab). The subject also wore a nose clip and was instructed to breathe normally through the mouth for the entire collection period. Expired gases were sampled every 15 seconds and oxygen uptake ($\dot{V}O_2$) was calculated as the average of two 15-second values. The subject performed an identical test the following day. To control for any measurement error due to

circadian rhythms (Folk, 1974; Reilly and Marshall, 1991), the test was performed at the same time of day and under identical environmental conditions.

2.6.2.b. Submaximal exercise test

Three subjects performed a 9-minute continuous dry-land arm-pulling exercise test on two occasions. The test used an arm-pulling swimming ergometer (swim bench). The subjects reported to the laboratory after being instructed to abstain from vigorous exercise and intake of food for at least two hours prior to the test. After completing a medical questionnaire, the subjects signed a consent form (Appendix A) and were allowed a free warm-up prior to the test. Then, the subjects were fitted with a mouthpiece connected to the COVOX Microlab analyser and a nose clip. The subjects adopted a prone posture on the ergometer and placed their hands in the hand paddles. The intensity of exercise was set constant at 30 W and the subjects began arm-pulling. No data were collected during the first three minutes of the exercise to allow the subjects to reach steady state conditions. After this period elapsed, oxygen uptake was sampled every 15 seconds using the on-line COVOX Microlab analyser. Oxygen uptake was computed for every 30 seconds as the average of two 15-second values. This test was repeated under the same environmental conditions as for the first test 48 hours later.

2.6.2.c. Maximal exercise test

The reliability of the COVOX Microlab gas analysis method for measuring maximal $\dot{V}O_2$ values was assessed in three subjects. The subjects performed a 9-minute treadmill running test on two occasions four days apart. To ensure accuracy of measurements, the subjects reported to the laboratory at the same time of day on both occasions. They were instructed to abstain from intake of food for at least two hours prior to the test. The subjects performed a 3-minute warm-up at a self-selected speed. Then they were fitted with a mouthpiece connected to direct gas

analysis equipment (COVOX Microlab) and also wore a nose clip. The intensity of exercise was set constant at 9.7 $km \cdot h^{-1}$ (2.69 $m \cdot s^{-1}$). To allow for steady state conditions, no data were collected during the first three minutes of the exercise test. After this period, oxygen uptake was sampled at 15-second intervals and was computed every 30 seconds as the average of two 15-second values. The same subjects repeated the test four days later under identical laboratory conditions.

2.6.2.e. Results

For the resting $\dot{V}O_2$ values the correlation between the absolute differences between the tests and their individual means was r=0.17, (P=0.56). These results are shown in Appendix B (Figure 2). After logarithmic transformation r= -0.02 (P=0.93). The systematic bias for the log data was –0.08 and the random error ± 0.24 (0.12 x 1.96). The limits of agreement are presented in Figure 3. For the resting, submaximal and maximal oxygen uptake values ($\dot{V}O_2$; $l \cdot min^{-1}$) the coefficients of variation (CV%) were 4.1%, 8.2% and 7.7%, respectively.

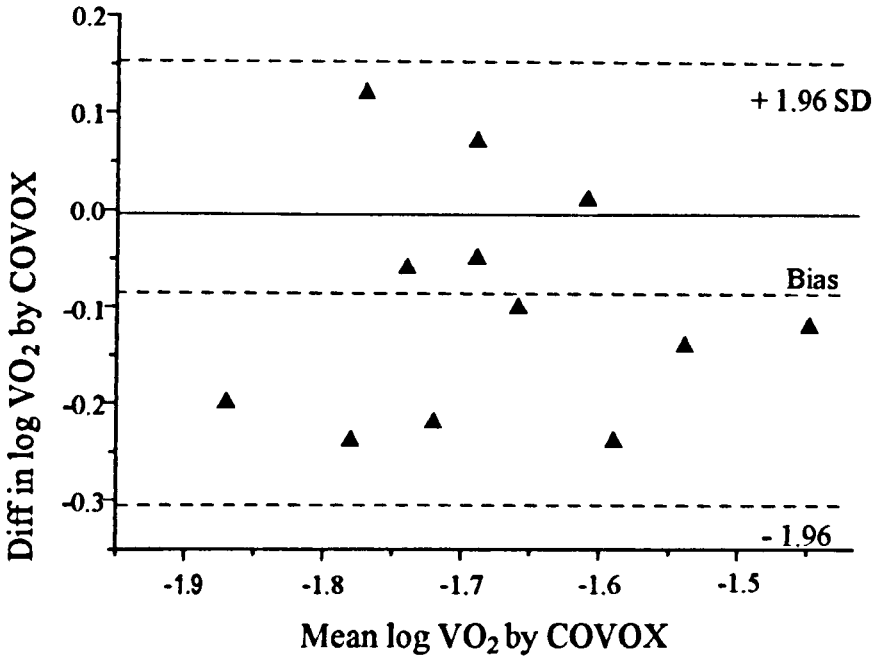


Figure 3. Logarithmic (natural) transformation of differences and their individual means (r=-0.02, P=0.93) for resting ($\dot{V}O_2$) values measured by the COVOX Microlab gas analysis method. The straight line indicates the zero line and the dashed lines indicate the bias (-0.08) and the random error (0.12 x 1.96 SD = 0.24). The limits of agreement are expressed as bias ± random error (-0.08 ± 0.24).

2.6.2.f. Discussion

The findings of this study demonstrated that the COVOX Microlab is a reliable method for measuring resting, submaximal and maximal oxygen uptake values. Unfortunately, there have not been any published studies on reliability of the COVOX Microlab method with which the findings of the present study can be compared. There have been studies that have used the COVOX Microlab to assess cardiorespiratory responses and mechanical efficiency during cycling (Coleman et al., 1998) and energy demands of competitive road race cycling (Coleman et al., 1998), but these authors did not report the reliability of this equipment. Alternatively, there have been studies that have assessed the reliability of other on-line gas analysis methods, such as the Aerosport KB1 portable metabolic measurement system (Unnithan et al., 1994) and the Sensormedics S2900Z metabolic cart (King et al., 1999). These studies have used a reference system or criterion method, -in both cases the Douglas bags method- to assess the validity, rather than the reliability, of these equipment.

For the resting oxygen uptake values, the reliability of the COVOX Microlab method was assessed using two techniques; the 'limits of agreement' (LOA) and the test re-test coefficient of variation (CV%). The measurement error of the COVOX Microlab that was calculated using the LOA was larger than the one calculated for the Douglas bags in the previous study of this thesis using the same technique (-0.08 ± 0.24 $l \cdot min^{-1}$ versus -0.002 ± 0.11 $l \cdot min^{-1}$). This difference is demonstrated in the corresponding CV% for the same values (4.1% versus 0.4%). However, these differences are small and therefore, one can conclude that the reliability of COVOX Microlab for measuring resting oxygen uptake values is acceptable.

The reliability of the COVOX Microlab in measuring submaximal oxygen uptake values was examined using the CV%. The CV% of 8.2% found in this study is higher than the 4% reported by the manufacturers (http:\\www.

covox.co.uk/repeatability). However, this 4% difference may be due to the exercise protocol. In this study, the subjects performed a 9-minute submaximal exercise bout on two separate occasions, whereas in the other study the subjects' steady state oxygen uptake was measured for one minute on five separate occasions over five consecutive days. Therefore, the CV% reported by the manufacturers might have been small due to possible learning effects (Martin et al., 2000).

The reliability of the COVOX Microlab in measuring maximal oxygen uptake values was also examined using the CV%. This value was 6.5% higher than the respective CV% calculated for maximal oxygen uptake values using the Douglas bags method (7.7% versus 1.2%). These findings suggest that the reliability of the COVOX Microlab method in measuring maximal oxygen uptake values is poorer than that of the Douglas bags for the same measurements. Nevertheless, these results also showed that the reliability of this on-line system is good with an average variability of 6.6%. This % variability is acceptable for clinical measurement (Bland and Altman, 1986).

2.6.3. Reliability of COSMED K2

The reliability of the COSMED K2 gas analysis method was assessed using the same procedure as described in the assessment of reliability of the Douglas bags method. The reliability of this measurement tool was assessed for resting, submaximal and maximal values of oxygen uptake. It was possible to calculate the 'limits of agreement' for the resting oxygen uptake values, whereas the reliability of the submaximal and maximal oxygen uptake values was examined using the coefficient of variation (CV%). The procedure used in collection of resting oxygen uptake data using the COVOX Microlab gas analysis system was the same as for the COSMED K2 analyser.

2.6.3.a. Submaximal exercise test

Two subjects performed a 9-minute submaximal dry-land arm-pulling test using a swim bench. The subjects signed an informed consent and were allowed a free warm-up prior to the test. During this period the COSMED K2 analyser was calibrated. The subjects were then fitted with a specially designed mouthpiece, which was used in assessment of $\dot{V}O_2$ in the third study presented in this thesis (see Chapter 5). This mouthpiece was connected to the COSMED K2 transmitter unit, which transmitted the data to the receiver unit (placed 5 m apart). The subjects adopted a prone posture on the swim bench and put their hands in the hand paddles. The intensity of exercise was set constant at 30 W and the subjects began arm-pulling. No data were collected during the first three minutes of the test to allow for steady state conditions. After this period, oxygen uptake was sampled every 5 seconds and computed for every 15 seconds as the average of three 5-second values. The subjects repeated the test two days later at the same time of day and under the same laboratory conditions.

2.6.3.b. Maximal exercise test

Two subjects performed a 6-minute whole-body incremental exercise test using a combined arm-leg ergometer. This involved co-ordinated arm-pulling and leg-kicking action. The subjects were given a 3-minute warm-up on the ergometer at an intensity of 20 W prior to the test. The COSMED K2 analyser was calibrated and the subjects were fitted with the apparatus as previously for the submaximal test. The intensity of exercise was then set at 30 W and would increase by 7.5 $W \cdot min^{-1}$ thereafter. Oxygen uptake was sampled every 5 seconds and computed for every 30 seconds as the average of six 5-second values. The subjects repeated the test three days later and under the same conditions.

2.6.3.c. Results

The measurement error was not found to be related to the magnitude of the measured variable for resting $\dot{V}O_2$ values measured by the COSMED K2 method. This was shown in the plot between absolute differences and their individual means, where there was no correlation between the variables ($r = -0.07$; $P=0.89$). These data are presented in Appendix B (Figure 3). The 'limits of agreement' (LOA) were calculated on these data. The systematic bias was 0.006 and the random error ± 0.05 (0.02 x 1.96). The LOA for the resting $\dot{V}O_2$ data are presented in Figure 4. For the resting, submaximal and maximal oxygen uptake values ($\dot{V}O_2$; $l \cdot min^{-1}$) the calculated coefficients of variation (CV%) were 4.7%, 9.6% and 8.9%, respectively.

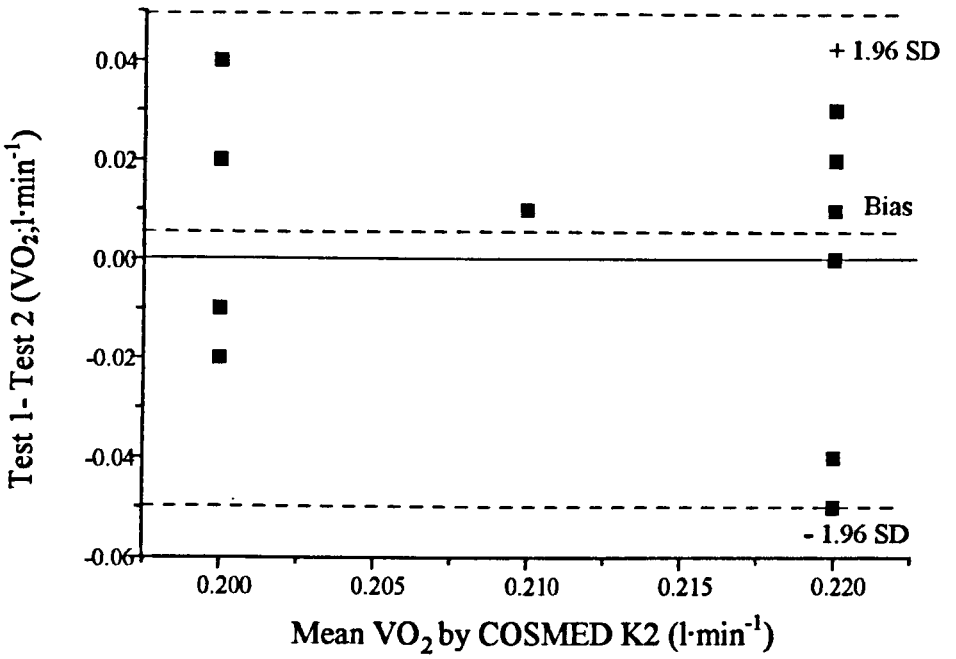


Figure 4. A Bland and Altman plot of the differences and their individual means for resting oxygen uptake $\dot{V}O_2$ values measured by the COSMED K2 gas analysis method. The straight line indicates the zero line and the dashed lines indicate the bias (0.006) and random error (0.02 x 1.96 SD = 0.05). The 'limits of agreement' are expressed as bias ± random error (0.006 ± 0.05).

2.6.3.d. Discussion

The findings of this study showed that, according to the coefficients of variation, the reliability of the COSMED K2 is affected by the magnitude of the measured values. This means that the reliability of this measurement tool decreases with increasing oxygen uptake values. It has been previously suggested that the COSMED K2 system cannot accurately assess $\dot{V}O_2$, as it does not assess carbon dioxide output (Bigard and Guezenec, 1995). Thus, for R-values (respiratory exchange ratio) exceeding 1.00 (i.e. where carbon dioxide production exceeds the rate of oxygen consumption) oxygen uptake is bound to be underestimated (Bigard and Guezenec, 1995). Therefore, this might serve as explanation for the 9.6% and 8.9% variability observed in this study for the submaximal and maximal oxygen uptake values, respectively.

There have been studies that have used the COSMED K2 analyser as the criterion method to assess the validity of other gas analysis methods. These studies have compared oxygen uptake between the COSMED K2 and the Quinton on-line method (Lothian et al., 1993) and also between the COSMED K2 and the Alpha Technologies VMM breath-by-breath analyser (Crandall et al., 1994). The findings of these studies have suggested that the COSMED K2 oxygen uptake measurements are valid only in light to moderate exercise intensities at sea level or at altitude (Bigard and Guezenec, 1995). However, the above studies have rather assessed the agreement between the COSMED K2 method and other direct methods of gas analysis. Nevill and Atkinson (1997) have postulated that a measurement tool can be valid only if it is reliable. In those studies the reliability of the measurement tool, to which the COSMED K2 was compared, were not reported.

2.6.4. Summary

The reliability of three gas analysis methods (Douglas bags, COVOX Microlab and COSMED K2) was assessed in this section. The reliability of all three gas analysis methods was examined for measuring resting, submaximal and maximal oxygen uptake values. The main technique used in assessment of reliability was the test re-test coefficient of variation (CV%); however, the 'limits of agreement' (LOA) were also calculated for the submaximal and maximal oxygen uptake values in all three methods. According to the findings, the method with the highest reliability was the 'Douglas bags' method. According to the findings, the reliability of this method was not affected by the magnitude of the measured values. This was demonstrated by the LOA and CV% values. These findings confirm previous notions about the reliability of the Douglas bags method (Wilmore and Costill, 1994).

The results of the COVOX Microlab reliability study suggested consistency of measurements across the different magnitudes of oxygen uptake values, with an average CV% of 6.6%. Despite this consistency, the COVOX Microlab is less reliable than is the 'Douglas bags' method. However, this equipment can be used in assessments of gas exchange variables, if the above variability is taken into account.

The findings of the COSMED K2 reliability study showed that the variability is affected by the magnitude of the measured oxygen uptake values. This is especially the case for the maximal oxygen uptake values, which has been attributed to the documented flaw in the design of this equipment. However, the CV% values for the submaximal and maximal oxygen uptake measurements are comparable to those of the COVOX Microlab method. In a subsequent section, the validity of the COVOX Microlab and the COSMED K2 will be examined against the highly reliable Douglas bags method. The results of the reliability studies for

the Douglas bags, COVOX Microlab and COSMED K2 gas analysis methods are shown in Tables 4 and 5.

Table 4. Limits of agreement (LOA) for resting oxygen uptake ($\dot{V}O_2$; $l \cdot min^{-1}$) values for the Douglas bags, COVOX Microlab and COSMED K2 gas analysis methods.

	Resting $\dot{V}O_2$ ($l \cdot min^{-1}$)
Douglas bags	-0.02 ± 0.11
COVOX Microlab	-0.08 ± 0.24
COSMED K2	0.006 ± 0.05

Table 5. Coefficients of variation (CV%) for resting, submaximal and maximal oxygen uptake ($\dot{V}O_2$; $l \cdot min^{-1}$) using the Douglas bags, the COVOX Microlab and the COSMED K2 gas analysis methods.

	Resting $\dot{V}O_2$	Submaximal $\dot{V}O_2$	Maximal $\dot{V}O_2$
Douglas bags	0.4%	4.0%	1.0%
COVOX Microlab	4.1%	8.2%	7.7%
COSMED K2	4.7%	9.6%	8.9%

2.6.5. Assessing Reliability of Blood Lactate Analysis Methods

2.6.5.a. Introduction

Blood lactate (HLa) has been documented as one the main determinants of endurance performance (Jacobs, 1986). There have been many investigations of the blood lactate responses to various forms of exercise in an attempt to explain improvements in performance (Stegman et al., 1982). The blood lactate responses to dry-land arm-pulling and leg-kicking exercise in swimmers were investigated in the first study presented in this thesis (see Chapter 3). The Yellow Springs International 2300 (YSI) lactate analyser was used in analysis of blood lactate. The reliability of this equipment was assessed prior to testing. In a subsequent chapter, the agreement of the YSI analyser with a reliable method of blood lactate analysis is examined. This reliable method is the 'Fluorimetric method', which has been shown to provide for accurate and rapid blood lactate measurements (Maughan, 1982). However, there have not been any published data on the reliability of the 'Fluorimetric method' and therefore, the reliability of this method will also be assessed in this section.

2.6.5.b. General procedure

The same blood sampling procedures were used for the Fluorimetric and the YSI methods. The blood sampling procedures included collection of blood samples from an ancetubital vein (via venepuncture) and from the middle finger (via finger-prick) of the subjects' preferred hand. It has been suggested previously that blood lactate concentration is higher in capillary (fingertip) than in venous blood in both resting and exercise conditions (el-Sayed et al., 1993), but larger amounts of blood can be obtained via venepuncture. To test the reliability of the Fluorimeter and the YSI methods in reading resting concentrations of blood lactate, it was necessary to obtain at least a 10-ml blood sample so that to make up several assays to be analysed by each method. It was not possible to obtain such a

large sample from the same finger-prick under resting conditions. The venepuncture procedure was solely used to obtain blood samples during resting conditions, whereas the finger-prick procedure was used to obtain blood samples during exercise. During exercise, it was possible to obtain several blood samples from the same finger-prick as exercise facilitates blood flow to the capillaries (McArdle et al., 1996). The venepuncture and finger-prick procedures were performed according to the 'Position Statement on the Physiological Assessment of the Elite Competitor' published by the British Association of Sports Sciences (Hale et al., 1988). The codes of practice for performing venepuncture and finger-prick blood sampling are described in detail in Appendix A.

Ten assays were analysed for low concentration of blood lactate using the Fluorimetric and the YSI methods, whereas eight assays were analysed for medium and high concentrations of blood lactate using the Fluorimetric and the YSI methods, respectively. The reliability of each method of blood lactate analysis to measure low, medium and high concentration of blood lactate was assessed using the test re-test coefficient of variation (CV%).

2.6.5.c. Low blood lactate concentration samples

The sample with low blood lactate concentration was collected from one subject using the venepuncture procedure. To ensure low concentration of lactate, the subjects had been instructed to refrain from vigorous activity for at least 24 hours prior to the sampling procedure. The blood sample obtained via venepuncture under resting conditions was collected in a 10-ml syringe. This sample was then divided equally into two tubes. One tube contained the sample to be analysed using the Fluorimeter and the other contained the sample to be analysed using the YSI method. The blood sample to be analysed using the Fluorimeter was deproteinised using perchloric acid (Maughan, 1982). The blood sample was then subdivided into ten smaller samples, which were frozen until they were analysed. The collection and analysis of the venepuncture blood sample using the

Fluorimeter was performed by a laboratory technician (see page 76-77). The sample to be analysed using the YSI was collected into ten disposable micro-haematocrit tubes (through capillary action), which were then emptied into 500-ul micro Eppendorf tubes (cuvettes). These samples were immediately analysed using the YSI method (see page 81). The collection and analysis of the YSI samples were performed by the author of this thesis. The analysis of blood lactate concentration using the Fluorimetric and the YSI methods was performed as described on pages 77 and 81, respectively.

2.6.5.d. Medium and high blood lactate concentration samples

Eight blood samples were obtained from one subject upon completion of the third stage of an incremental running test for the determination of OBLA (Onset of Blood Lactate accumulation) on two separate occasions two days apart. The OBLA test consisted of four 4-minute stages at increasing running speeds (8, 9, 10 and 11 $km \cdot h^{-1}$). It was expected that a running speed of 11 $km \cdot h^{-1}$ would elicit a blood lactate concentration of approximately 3-5 $mmol \cdot l^{-1}$ for this particular individual who was untrained. The blood samples were collected in eight micro-haematocrit tubes, four of which were analysed using the Fluorimeter, whereas the other four samples were analysed using the YSI analyser. The test was repeated two days later and eight further samples were obtained using the same procedure. Again, four samples were analysed using the Fluorimeter and four using the YSI analyser.

To obtain samples with high concentration of blood lactate, one subject completed a maximal running exercise test ($\dot{V}O_{2max}$) on a motorised treadmill. The speed was kept constant and the gradient increased by 2.5% until the subjects reached exhaustion. Eight blood samples were taken from the same finger-prick immediately upon completion (within 2 minutes) of the test using the finger-prick procedure. Four of these samples were analysed using the Fluorimeter and four

using the YSI analyser. The subject repeated the test at the same time of day four days later. A further eight samples were obtained and analysed as described above.

2.6.5.e. Results

The results of the blood sample analysis are shown in the following table.

Table 6. Mean ± SD and coefficients of variation (CV%) for low (n=10), medium (n=8) and high (n=8) lactate concentration ($mmol \cdot l^{-1}$) blood samples analysed with the Fluorimeter and YSI methods.

	Fluorimeter		**YSI**	
Concentration	**Mean ± SD ($mmol \cdot l^{-1}$)**	**CV (%)**	**Mean ± SD ($mmol \cdot l^{-1}$)**	**CV (%)**
Low	0.55 ± 0.02	**3.63**	0.32 ± 0.03	**9.37**
Medium	4.71 ± 0.13	**2.76**	3.78 ± 0.05	**1.32**
High	7.11 ± 0.20	**2.81**	5.22 ± 0.19	**3.66**

2.6.5.f. Discussion

The findings of this study showed that both blood lactate analysis methods have small variability irrespective of lactate concentration. This is especially the case for the Fluorimetric method, which also demonstrated high consistency in measuring different blood lactate concentrations. These findings agree with those of previous studies (Maughan, 1982; Jonkers et al., 1982). In this study, the coefficient of variation of 3.63% found for low blood lactate concentration compares well with that reported by Maughan (1982) for the same blood lactate concentration (CV%=2.53%, mean sample concentration: 0.83 $mmol \cdot l^{-1}$). Also, Jonkers et al. (1982) examined the within-day variability of a flow-fluorimeter and reported a CV% of 3.8%.

There was quite small variability in the YSI measurements of medium and high blood lactate concentrations. These values are comparable to those of the Fluorimetric method for the same blood lactate concentrations. The variability of the YSI was three times greater than that of the Fluorimetric method, when measuring low concentration blood lactate values (9.37% versus 3.63%). Bishop et al. (1992) suggested that the YSI has a tendency for large discrepancies at resting values. In a different study, Bishop et al. (1992) assessed the reliability of the YSI method in reading high concentration of blood lactate and reported a CV% of 2.0%. This % is comparable to the one obtained in this study for high concentration of blood lactate (3.6%).

2.7. Assessing Validity of Measurement Tools

2.7.1. Introduction

Validity has been defined as the ability of the measurement tool to reflect what it is designed to measure (Safrit and Wood, 1989). Therefore, new equipment needs to be assessed for its validity before being used in measurements. As it was shown in the previous section, Bland and Altman (1986) have proposed a technique according to which the new equipment is evaluated by comparison against an established measurement tool and the measurement error is calculated. This technique can also be used to assess reliability and it is known as the 'limits of agreement' (LOA). If the calculated LOA values are small then the new equipment can be confidently used in clinical measurement. Moreover, the new equipment can be used to replace the 'old' measurement tool.

Mullineaux et al. (1999) documented that comparative analysis of data has been proposed as appropriate via the use of tests, such as Pearson Product Moment correlation coefficients (Graveter and Wallnau, 1996), intraclass correlation coefficients (ICC; Vincent, 1999), 'limits of agreement' (LOA; Bland, 1995), least squares regression (LSR; Graveter and Wallnau, 1996) and least products regression (LPR; 1997). The same workers also stated that the principal limitation with the majority of these tests -except for LOA and LPR- is that they do not provide information to assess both fixed and proportional biases. Thus, the assessment of fixed and proportional biases in comparative studies must be undertaken using either LOA or LPR (Mullineaux et al., 1999).

The LOA was selected as the appropriate method to assess the validity of different measurement tools in this thesis. The LOA is an approach based on graphical techniques and simple calculations. The procedure for calculating the LOA has been described in an earlier section (pages 86-87). The validity of the gas (COVOX Microlab and COSMED K2) and blood lactate analysis (YSI) methods used in the

different studies of this thesis will be assessed against a criterion method. The validity of the COVOX Microlab and COSMED K2 measurements will be assessed against measurements obtained using the Douglas bags method, whereas the validity of the YSI measurements will be assessed against the measurements obtained using the Fluorimetric method.

2.7.2. Assessing Validity of Gas Analysis Methods

2.7.2.a. General procedure

The most widely used method in the analysis of expired air is the Douglas bags method. This method involves collection of expired gases in an airtight bag. The volume of expired gas is then analysed for its O_2 and CO_2 content and simple calculations are carried out to compute oxygen uptake (a detailed description of this procedure has been given on page 57). The Douglas bags method is the simplest and oldest method and it is probably the most accurate method to-date (Wilmore and Costill, 1999). The only disadvantage of the Douglas bag method is that it is relatively slow and permits only a few measurements of expired gases to be performed within a single testing session. The reliability of this method to measure resting, submaximal and maximal oxygen uptake values was examined in the previous section. It was shown that this method is highly reliable in measuring oxygen uptake of all concentrations. This confirms the consensus of research that the Douglas bags method is a well-established method in measurements of oxygen uptake.

The COVOX Microlab is an on-line gas analysis system that has been recently developed. The main advantage of this system is its design enables expired gases to be collected in a mixing chamber, where they are immediately analysed for their O_2 and CO_2 content. Also, this method has the advantage of computing oxygen and carbon dioxide kinetics during testing. This information is displayed on screen of an IBM compatible computer and this enables close monitoring of respiratory parameters during exercise. However, apart from the manufacturer's report on validation of the

COVOX Microlab, there are no other published data on the validity of measurements of this equipment.

The COSMED K2 is a portable, telemetric oxygen analyser. In short, the technical specifications of this system present the following advantages. Its combined weight (transmitter and receiver unit and battery pack) is approximately 850 kg and therefore, can be used to measure oxygen uptake during sporting activities in the field. For the purposes of the third study in this thesis, the COSMED K2 was used for measurements of oxygen uptake in a swimming pool. The in-built turbine can measure flow rates (up to 300 $l \cdot min^{-1}$). Expired air can be sampled at different time intervals (5, 15, 30 seconds) and oxygen uptake is internally computed. The data are telemetrically transmitted to the receiver unit and a print out is immediately available. There have been studies that have assessed the validity of this system (Lothian et al., 1993; Crandall et al., 1994). However, these studies did not use the 'limits of agreement' (LOA).

As suggested in a previous paragraph, the 'new' system (COVOX Microlab) has to be assessed for its validity before it can be used with confidence in measurements of respiratory variables. Oxygen uptake was the respiratory parameter that was assessed in all the three studies of this thesis. Therefore, the validity of COVOX Microlab and COSMED K2 to measure oxygen uptake will be assessed within the context of this section. This process will involve comparisons of resting, submaximal and maximal oxygen uptake readings between the 'new' methods (COVOX Microlab and COSMED K2) and the 'old' method (Douglas bag).

The results of the measurements will be first examined for normality (homoscedasticity or heteroscedasticity of data). If the data are found to be heteroscedastic, an appropriate transformation (Tabachnick and Fidell, 1996) will be applied and the LOA will be calculated on the transformed data and exepressed as ratios. On the other hand, if the data are found to be homoscedastic, the LOA will be

calculated on the same data. This procedure was adopted from Nevill and Atkinson (1997) and has been described in detail in the previous section (reliability of measurement tools).

2.7.3. Validity of the COVOX Microlab method

The degree of agreement between the COVOX Microlab and the Douglas bag method was assessed for low, medium and high oxygen uptake values. The COVOX Breathing Circuit (Diagram 9) was used to enable measurements of expired gases using the Douglas bags and the COVOX Microlab methods during the same exercise tests. The COVOX Microlab breathing circuit is specially designed to enable a Douglas bag to be connected in-line after the expired air enters the mixing chamber. The accuracy of the data reported by the COVOX Microlab was tested by directing expired air into the mixing chamber and then switching to the Douglas bag for manual independent analysis. The protocol used involved sampling of expired air at 'steady state' (O_2 supply equals O_2 demand) conditions.

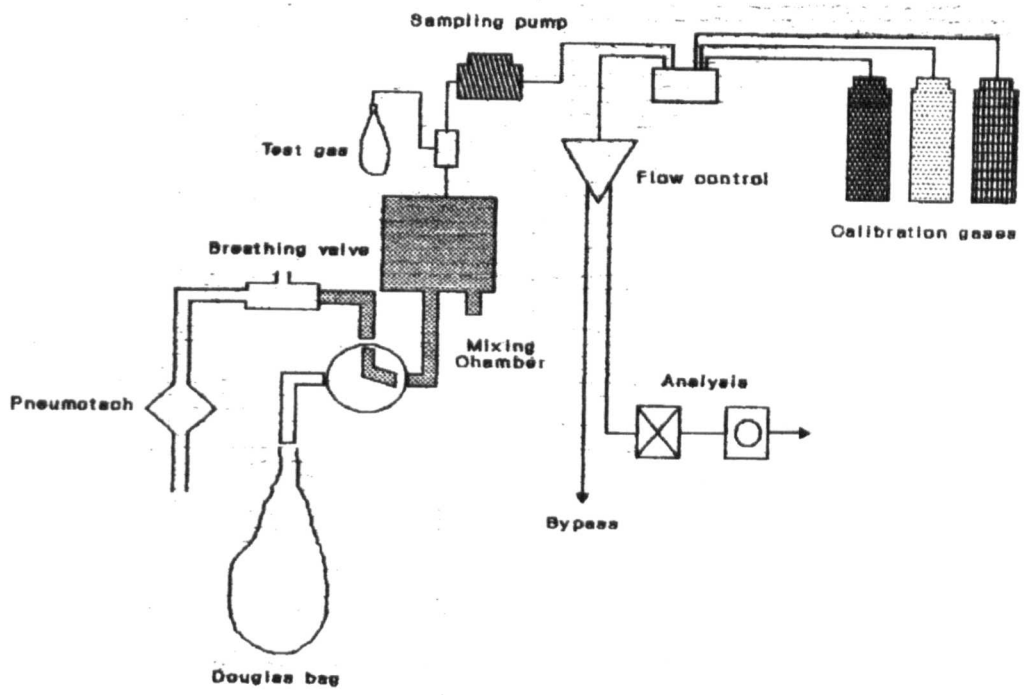


Diagram 9. The COVOX Microlab breathing circuit (from manufacturer's Instructions Manual) showing the mixing chamber, sampling pump and the connection point for the Douglas bag.

2.7.3.a. Resting measurements

First, the COVOX Microlab was calibrated and ten Douglas bags were evacuated. Then, a Douglas bag was connected in-line with the expiratory port on the COVOX Microlab analyser. One subject was fitted with a T-shape mouthpiece (Hans Rudolf, Series 2700) connected to the COVOX Microlab analyser and a nose clip. The subject adopted a supine posture on a bench and was instructed to breathe normally through the apparatus for a period of twenty minutes. No data were collected during the first minute to allow the system to be purged with the subject's expirate. After this period elapsed, the subject's expirate was passed through the COVOX for one minute. Oxygen uptake was sampled every 15 seconds and computed for the entire minute as the average of four 15-second values. Then the expirate was directed into the Douglas bag and a 60-second sample was obtained. The system was switched

back to COVOX sampling and a new Douglas bag was replaced at the expiratory port. The same procedure was repeated until ten Douglas bags were filled with expirate. Ten oxygen uptake values were computed and were displayed on screen of the COVOX Microlab analyser. The Douglas bags were immediately analysed for their oxygen content using the procedure described on pages 57-58.

2.7.3.b. Submaximal exercise test

The COVOX Microlab and Douglas bags were prepared as for the resting measurements. Three subjects performed a discontinuous incremental dry-land arm-pulling exercise test. The exercise test comprised four 5-minute stages at increasing intensities. After the subjects were fitted with the mouthpiece and nose clip, they adopted a prone posture on the swim bench. A Douglas bag was connected at the expiratory port of the COVOX Microlab analyser. The subjects put their hands in the hand paddles. For the first stage, the intensity of exercise was set constant at 20 W and at the command 'go' the subjects began arm-pulling. No data were collected during the first three minutes of each stage to allow for steady state conditions. Expired gases were collected for one minute during the 3^{rd}-4^{th} minute of each stage using the COVOX analyser. Oxygen uptake was sampled every 15 seconds and calculated for the entire minute as the average of four 15-second values. The expiratory port was then opened and the subject's expirate was directed into the Douglas bag for one minute during the 4^{th}-5^{th} minute of the same stage. At the end of this collection period the Douglas bag was closed, disconnected from the expiratory port and immediately taken for analysis. A new Douglas bag was replaced at the expiratory port. The intensity was set constant at 30 W and increased by 10 W at the beginning of each stage thereafter. The same procedure was followed for the remaining stages of the exercise test. In total, there were twelve oxygen uptake values determined by the Douglas bags method and another twelve determined by the COVOX Microlab analyser.

2.7.3.c. Maximal exercise test

Three subjects performed a discontinuous incremental running exercise test on a motorised treadmill. The test comprised four 5-minute stages at increasing running speeds. The subjects performed a warm-up at a self-selected speed and then rested for 5 minutes. After this period, the subjects were fitted with the breathing apparatus (mouthpiece and nose clip). For the first stage, the subjects run at a steady speed of 8.0 $km \cdot h^{-1}$ (2.22 $m \cdot s^{-1}$) for five minutes. The subjects breathed through a mouthpiece that was connected to the COVOX analyser. A Douglas bag had been connected in-line after the mixing chamber. Expired air was collected into the Douglas bag for 60 seconds throughout the 3^{rd}–4^{th} minute and into the COVOX analyser for 60 seconds throughout 4^{th}–5^{th} minute of exercise. At the end of the stage, a new Douglas bag was replaced in the breathing circuit. The subject then rested for four minutes. For the second, third and fourth stage of the test the speed was set constant at 9.7, 11.3 and 12.9 $km \cdot h^{-1}$ (2.69, 3.14 and 3.58 $m \cdot s^{-1}$), respectively. The same procedure for collection of expired air was repeated for each of the remaining stages of the test. This protocol allowed collection of expired air at incremental intensities of exercise using the COVOX and the Douglas bag method and oxygen uptake was computed for every minute of the collection with each method.

2.7.3.d. Results

For the resting oxygen uptake values ($\dot{V}O_2$; ranks) the correlation coefficient of the absolute differences between the two methods (Douglas bags-COVOX Microlab) and their individual means ($\dot{V}O_2$; $l \cdot min^{-1}$) showed that the measurement error was additive ($r = 0.10$; $P = 0.65$). These results are shown in Appendix C (Figure 1). The calculated LOA for the 95% confidence interval (C.I.) were 0.001 ± 0.03 $l \cdot min^{-1}$ (bias ± random error) and are presented in Figure 5. These LOA showed that the COVOX Microlab was 0.04 $l \cdot min^{-1}$ above or -0.02 $l \cdot min^{-1}$ below the Douglas bags measurements.

For the submaximal oxygen uptake values ($\dot{V}O_2$; ranks) the correlation coefficient of the absolute differences between the two methods (Douglas bags-COVOX Microlab) and their individual means ($\dot{V}O_2$; $l \cdot min^{-1}$) showed that the measurement error was additive (r= 0.05; P= 0.83). These results are shown in Appendix C (Figure 2). The calculated LOA for the 95% confidence interval (C.I.) were -0.21 ± 0.11 $l \cdot min^{-1}$ (bias ± random error) and are presented in Figure 6. These LOA showed that the COVOX Microlab was -0.10 $l \cdot min^{-1}$ above or -0.32 $l \cdot min^{-1}$ below the Douglas bags measurements.

For the maximal oxygen uptake values ($\dot{V}O_2$; ranks), the correlation coefficient of the absolute differences between the two methods (Douglas bags-COVOX Microlab) and their individual means ($\dot{V}O_2$; $l \cdot min^{-1}$) showed that the measurement error was multiplicative (r= 0.44; P= 0.15). These results are shown in Appendix C (Figure 3). The data were logarithmically transformed and the calculated LOA for the 95% confidence interval (C.I.) were: 0.004 ± 0.02 $l \cdot min^{-1}$ (bias ± random error). These data are presented in Figure 7. The antilogs of these values showed that the mean bias ± random error on the ratio scale were 1.00 ± 1.02.

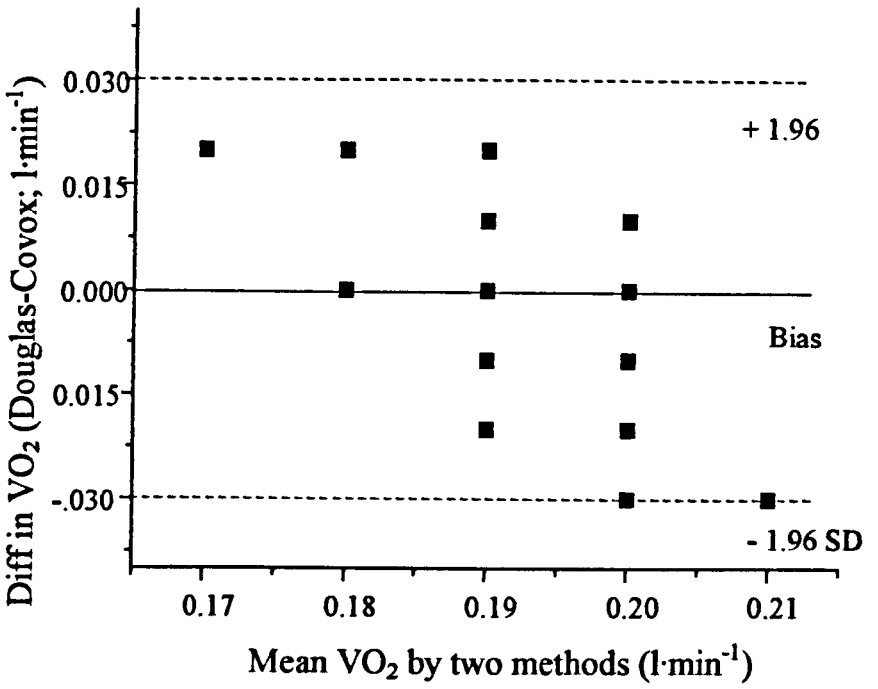


Figure 5. A Bland and Altman plot of the differences in resting oxygen uptake ($\dot{V}O_2$; $l \cdot min^{-1}$) between two methods (Douglas bags-COVOX Microlab) and their individual means ($\dot{V}O_2$; $l \cdot min^{-1}$). The LOA (95% C.I.; dashed lines) are shown as bias ± random error of measurement (0.001 ± 0.03). The straight line indicates the zero line.

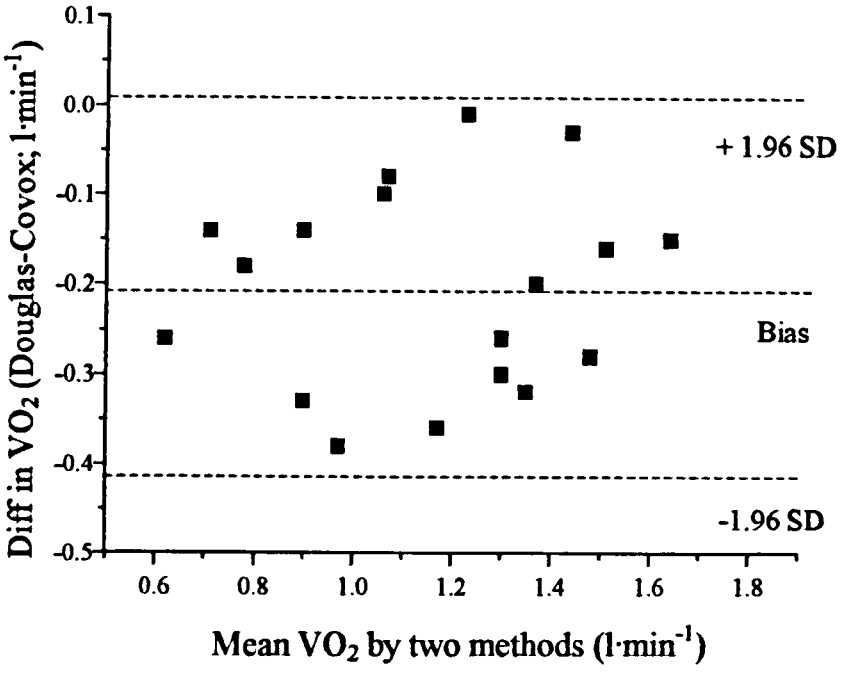


Figure 6. A Bland and Altman plot of the differences in submaximal oxygen uptake ($\dot{V}O_2$; l·min^{-1}) between two methods (Douglas bags-COVOX Microlab) and their individual means ($\dot{V}O_2$; l·min^{-1}). The LOA (95% C.I.; dashed lines) are shown as bias ± random error (-0.21 ± 0.11). The zero line coincides with the upper limit of the measurement error (+ 1.96 SD).

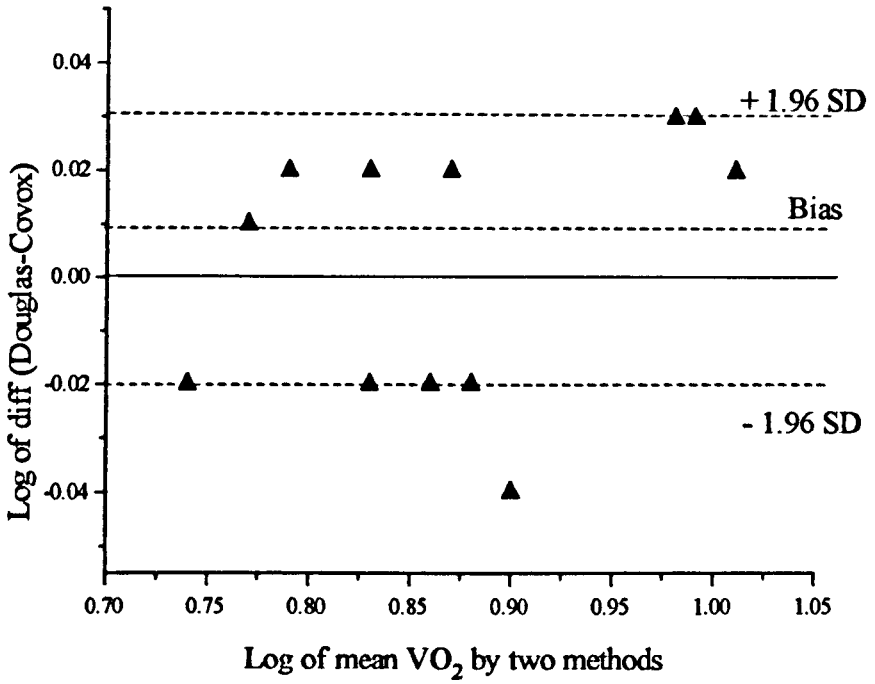


Figure 7. A Bland and Altman plot of the differences in maximal oxygen uptake ($\dot{V}O_2$; $l \cdot min^{-1}$) between two methods (Douglas bags-COVOX Microlab) and their individual means ($\dot{V}O_2$; $l \cdot min^{-1}$). The LOA (95% C.I.; dashed lines) are shown as bias ± random error (0.04 ± 0.02). The straight line indicates the zero line.

2.7.3.e. Discussion

The findings of this study demonstrated that the COVOX Microlab is a valid method to measure resting, submaximal and maximal oxygen uptake. The LOA values were narrow enough to warrant good agreement with the Douglas bags method across different magnitude oxygen uptake values. However, there are no published data on validity of the COVOX Microlab with which to compare the findings of this study. The only sources of comparison are validation data reported by the manufacturers (http:www.covox/reliability), where submaximal values of oxygen uptake obtained with the COVOX Microlab were compared to respective values obtained with the Douglas bags method. There was a CV% of 4% in that study, which indicates good agreement. Nevertheless, this value can not be directly compared to the LOA presented here.

The COVOX Microlab has been used in a few studies to assess respiratory parameters during exercise (Balmer and Coleman, 1997; Coleman et al., 1998), but these studies did not assess the validity of this equipment. Alternatively, studies that have assessed the validity of other gas analysis equipment by comparison with the Douglas bags method (Unnithan et al., 1994; Leaf and MacRae, 1995; King et al., 1999) have used the correlation coefficient to examine the measurement error. However, the use of the correlation coefficient to assess validity has been deemed inappropriate (Bland and Altman, 1986).

2.7.4. Validity of the COSMED K2 method

2.7.4.a. Resting measurements

First, the COSMED K2 was calibrated and ten Douglas bags were evacuated. The gas analysers used in analysis of expired in the Douglas bags were also calibrated. One subject was fitted with the COSMED K2 face mask and receiver unit and then adopted a supine posture on a bench. Expired air was conveyed through the facemask to a turbine flow meter. Part of the expired air was sampled from a pick-up located near the turbine and fed into the transmitter, where O_2 concentration was detected by a polarographic sensor (Kawakami et al., 1992). A respiratory hose was connected to the turbine and to the other end to a purpose-built Douglas bag rack (Plate 9). The operation of this device has been given on page 76. The purpose of using this bag rack instead of individual Douglas bags was to enable continuous collection of expirate from one bag to another at the same time with COSMED K2. It was possible using this bag rack to switch from bag to bag without interruption by manipulating the in-built valves. This bag rack operated by a computer program (De Montfort University Bedford, Bedford, UK), which measured the exact collection time (s) into each of the Douglas bags. First, the subject breathed through the apparatus for six minutes. During this period expired air was sampled by the COSMED K2 every 15 seconds and was collected into each of the six Douglas bags for 60 seconds. When all six Douglas bags were filled, they were detached from the bag rack and immediately taken for analysis. Four empty Douglas were replaced at the expiratory ports on the bag rack, the computer program was reset and a second collection period begun. This period lasted four minutes until four Douglas bags were filled with expired air. The time taken to replace the Douglas bags and reset the computer program was accounted for in the COSMED K2 readings. Expired air in the ten Douglas bags was analysed according to the procedure described on page 57 and oxygen uptake ($\dot{V}O_2$) was computed for every minute of the collection period. Ten $\dot{V}O_2$ values were obtained by the COSMED K2 readings as the average of four 15-second values for every minute of the collection period. Eventually, there were two sets of ten $\dot{V}O_2$

values obtained with each method. These values were used to assess the agreement between the COSMED K2 and the Douglas bags for resting $\dot{V}O_2$ measurements.

2.7.4.b. Submaximal exercise test

The COSMED K2 and the O_2 and CO_2 analysers used in the analysis of expired air in the Douglas bags were calibrated prior to testing. Two subjects performed a 9-minute submaximal running test on a motorised treadmill (Powerjog MX, 2000). First, the subjects performed a warm-up at a self-selected speed for three minutes. Then, they were fitted with the COSMED K2 facemask and had the receiver unit attached to their chest. Six Douglas bags were evacuated and then were connected to the expiratory ports on the bag rack (as described for the resting measurements). Treadmill speed was set constant at 8 $km \cdot h^{-1}$ (2.22 $m \cdot s^{-1}$) and the subjects began running. No data were collected during the first three minutes of the exercise test to allow for steady state conditions. After this period, expired air was sampled by COSMED K2 every 15 seconds and collected into Douglas bags for 60 seconds. After the test, the expired air in the Douglas bags was analysed for its O_2 and CO_2 concentration and six $\dot{V}O_2$ values were computed. Also, six $\dot{V}O_2$ values were computed for COSMED K2 as the average of four 15-second values for every minute of the collection period. Eventually, there were two sets of six $\dot{V}O_2$ values to be compared for agreement between the two methods.

2.7.4.c. Maximal exercise test

The COSMED K2 and the analysers used in the analysis of expired air in the Douglas bags were calibrated prior to testing. Two subjects performed a 9-minute maximal running test on a motorised treadmill (Powerjog MX, 2000). The subjects were allowed a free warm-up prior to testing. Treadmill speed was set constant at 12.9 $km \cdot h^{-1}$ (3.58 $m \cdot s^{-1}$). The subjects were fitted with the COSMED K2 apparatus and Douglas bags were arranged as for the submaximal test. Expired air was collected continuously for six minutes throughout the 3^{rd}-9^{th} minute using the two methods. The

same procedures for analysis and computation of $\dot{V}O_2$ were used (as described for the submaximal exercise test).

2.7.4.d. Results

For the resting oxygen uptake values ($\dot{V}O_2$; ranks) the correlation coefficient of the absolute differences between the two methods (Douglas bags-COSMED K2) and their individual means ($\dot{V}O_2$; $l \cdot min^{-1}$) showed that the measurement error was additive (r= -0.17; P= 0.62). These results are shown in Appendix C (Figure 4). The calculated LOA for the 95% confidence interval (C.I.) were 0.04 ± 0.015 $l \cdot min^{-1}$ (bias ± random error) and are presented in Figure 8. These LOA showed that the COSMED K2 was 0.055 $l \cdot min^{-1}$ above or 0.025 $l \cdot min^{-1}$ below the Douglas bags measurements.

For the submaximal oxygen uptake values ($\dot{V}O_2$; ranks) the correlation coefficient of the absolute differences between the two methods (Douglas bags-COSMED K2 Microlab) and their individual means ($\dot{V}O_2$; $l \cdot min^{-1}$) showed that the measurement error was additive (r= 0.14; P= 0.56). These results are shown in Appendix C (Figure 5). The calculated LOA for the 95% confidence interval (C.I.) were 0.01 ± 0.07 $l \cdot min^{-1}$ (bias ± random error) and are presented in Figure 9. These LOA showed that the COSMED K2 was 0.08 $l \cdot min^{-1}$ above or 0.06 $l \cdot min^{-1}$ below the Douglas bags measurements.

For the maximal oxygen uptake values ($\dot{V}O_2$; ranks) the correlation coefficient of the absolute differences between the two methods (Douglas bags-COVOX Microlab) and their individual means ($\dot{V}O_2$; $l \cdot min^{-1}$) showed that the measurement error was multiplicative (r= 0.35; P= 0.26). These results are shown in Appendix C (Figure 6). These data were logarithmically transformed and the LOA for the 95% confidence interval (C.I.) were 0.025 ± 0.13 $l \cdot min^{-1}$ (bias ± random error) and are presented in

Figure 10. These LOA showed that the COSMED K2 was 0.155 $l \cdot min^{-1}$ above or -0.105 $l \cdot min^{-1}$ below the Douglas bags measurements.

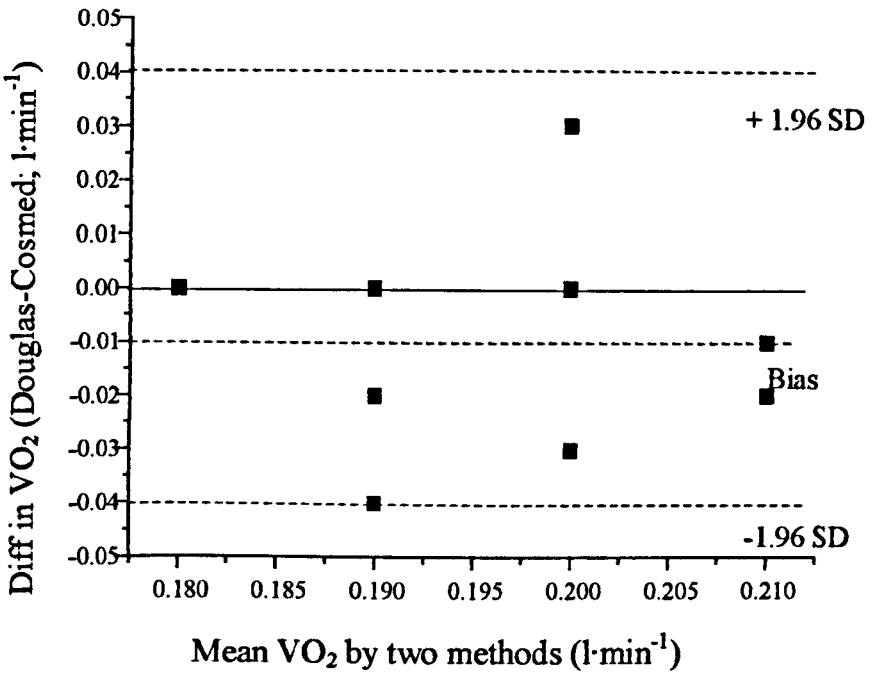


Figure 8. A Bland and Altman plot of the differences in resting oxygen uptake ($\dot{V}O_2$; $l \cdot min^{-1}$) between two methods (Douglas bags-COSMED K2) and their individual means ($\dot{V}O_2$; $l \cdot min^{-1}$). The LOA (95% C.I.; dashed lines) are shown as bias ± random error (-0.04 ± 0.015). The straight line indicates the zero line.

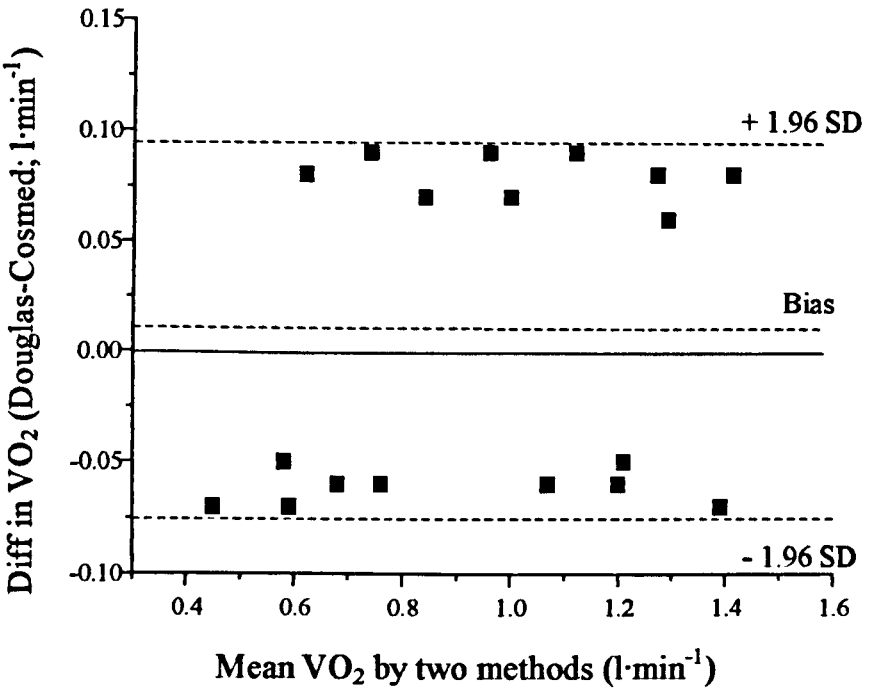


Figure 9. A Bland and Altman plot of the differences in submaximal oxygen uptake ($\dot{V}O_2$; $l \cdot min^{-1}$) between two methods (Douglas bags-COSMED K2) and their individual means ($\dot{V}O_2$; $l \cdot min^{-1}$). The LOA (95% C.I.; dashed lines) are shown as bias ± random error (0.01 ± 0.07). The straight line indicates the zero line.

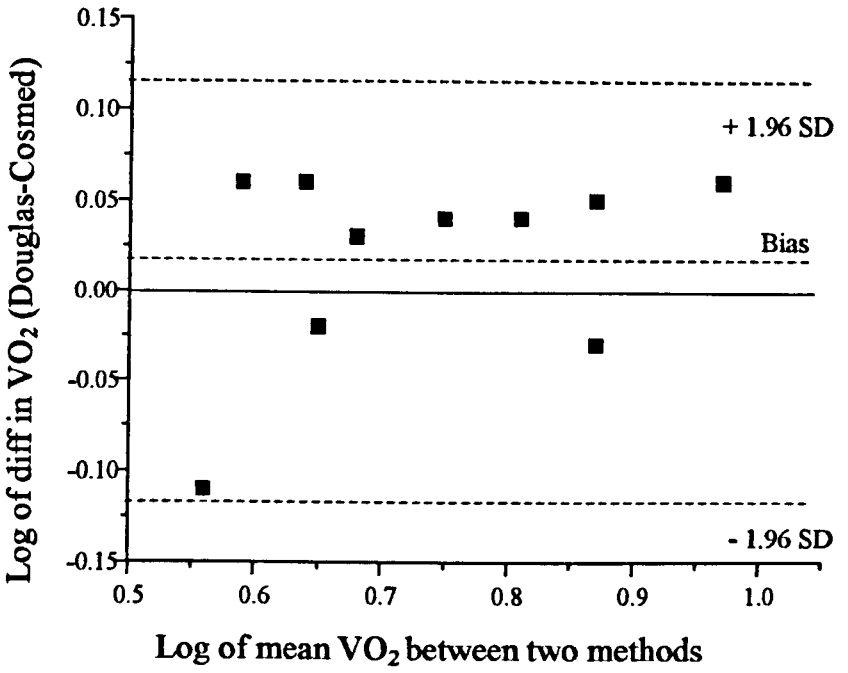


Figure 10. A Bland and Altman plot of the log transformed differences in maximal $\dot{V}O_2$ between two methods (Douglas bags-COSMED K2) and their log transformed individual means. The LOA (95% C.I.; dashed lines) are shown as bias ± random error (0.025 ± 0.13). The straight line indicates the zero line.

2.7.4.e. Discussion

The findings of this study showed that the validity of COSMED K2 decreases with increasing oxygen uptake values. The LOA values were narrower for resting and submaximal oxygen uptake, but larger for maximal oxygen uptake. These findings agree with the notion that has been suggested previously, where COSMED K2 underestimates oxygen uptake at high intensities of exercise. Lothian et al., (1993) assessed the validity of COSMED K2 by comparing oxygen uptake with the Quinton on-line analyser. It was found that, at low workloads, both methods gave approximately the same measure of oxygen uptake, whereas at peak oxygen uptake the COSMED K2 measured 22.2% lower than the Quinton. It has been suggested hat the validity of COSMED K2 is compromised by limitations inherent to the system, when measuring respiratory parameters at high intensities of exercise (Crandall et al., 1994). However, these limitations can be minimised if a RER (respiratory exchange ratio) correction factor is introduced (Crandall et al., 1994).

2.7.5. Summary

The results of the COVOX Microlab and COSMED K2 validation studies are presented in the Table 7.

Table 7. Limits of agreement (LOA; bias ± random error) for COVOX Microlab-Douglas bags and COSMED K2-Douglas bags for resting, submaximal and maximal oxygen uptake ($\dot{V}O_2$; $l \cdot min^{-1}$).

	Resting $\dot{V}O_2$ ($l \cdot min^{-1}$)	Submaximal $\dot{V}O_2$ ($l \cdot min^{-1}$)	Maximal $\dot{V}O_2$ (ratio scale)
COVOX - D. bags	0.001 ± 0.03	-0.21 ± 0.11	1.00 ± 1.02
COSMED - D. bags	0.04 ± 0.02	0.01 ± 0.07	1.02 ± 1.14

2.7.6. Assessing Validity of Blood Lactate Analysis Methods

2.7.6.a. Validity of the YSI method

The validity of the YSI (Yellow Springs International, 2300, Stat Plus) lactate analyser was assessed by comparing different lactate concentration values to respective values determined by the Fluorimetric method. This method has been established for its precision in detecting lactate fluorescence; hence the name Fluorimeter. The validity of the YSI lactate analysis method was assessed for three concentrations of lactate: a) low, b) medium, and c) high.

2.7.6.b. Low blood lactate concentration samples

To ensure low concentration of blood lactate, ten subjects refrained from vigorous exercise for at least two days prior to testing. Upon their visit to the laboratory all subjects were screened for blood-borne diseases through completion of a medical questionnaire (Appendix A). To prepare the sampling site, subjects immersed their non-dominant hand in luke warm water for two minutes. This procedure was used in order to arterialise the capillaries and facilitate blood flow to the tip of the finger. All blood samples were collected by a trained laboratory technician. Blood sampling was performed according to approved Safety Procedures (see Appendix A). The tip of one finger was swabbed with 70% alcohol. A pin-prick was made to the finger tip using an Autolet device and the first drop of blood was wiped away with cotton wool. Two blood samples were collected from this finger prick. These samples were collected into micro-haematocrit tubes through capillary action. The site was then swabbed and covered with a plaster. One tube was emptied into a cuvette and was immediately analysed using the YSI analyser. The contents of the other tube were emptied into another cuvette containing perchloric acid. This sample was decanted and frozen, until analysed (within 48 hours from collection) using the Fluorimetric method (Maughan, 1982).

2.7.6.c. Medium blood lactate concentration samples

Ten subjects performed a discontinuous incremental running exercise test on a motorised treadmill (Powerjog, MX 2000). The subjects completed a medical questionnaire and then were allowed a free warm-up at a self-selected speed. The test consisted of four 3-minute stages at increasing speeds. For the first stage, the speed was set at 8.0 $km \cdot h^{-1}$ (2.22 $m \cdot s^{-1}$). Upon completion of this stage the treadmill was stopped and a blood sample was obtained from the subjects' finger. The same procedure for collection and analysis of blood samples using the YSI and the Fluorimeter was used as for low lactate concentration. For the remaining stages of the test, the treadmill speed was set at 9.7, 11.3 and 12.9 $km \cdot h^{-1}$ (2.69, 3.14 and 3.58 $m \cdot s^{-1}$, respectively). Three blood samples were obtained in the same manner as for the sampling of low concentration of lactate.

2.7.6.d. High blood lactate concentration samples

Ten subjects performed a maximum running exercise test on a motorised treadmill for the determination of maximum oxygen uptake test ($\dot{V}O_{2max}$). One blood sample was collected directly from each subject's finger within one minute from completion of the test using the procedure described above. The blood samples were analysed with the YSI and Fluorimetric method. Two sets of ten values of high lactate concentration were compared for agreement.

2.7.6.e. Results

For the low lactate concentration (HLa) measurements, the correlation coefficient of the absolute differences between the two lactate analysis methods (Fluorimeter-YSI) and their individual means (HLa; $mmol \cdot l^{-1}$) showed that the measurement error was additive ($r=0.08$; $P=0.80$). These results are shown in Appendix C (Figure 7). The calculated LOA for the 95% confidence interval (C.I) were 0.03 ± 0.06 $mmol \cdot l^{-1}$ (bias ± random error) and are presented in Figure 11.

For the medium concentration HLa measurements, the correlation coefficient of the absolute differences between the two lactate analysis methods (Fluorimeter-YSI) and their individual means (HLa; $mmol \cdot l^{-1}$) showed that the measurement error was additive ($r=-0.15$; $P=0.64$). These results are shown in Appendix C (Figure 8). The calculated LOA for the 95% C.I were 0.4 ± 0.6 $mmol \cdot l^{-1}$ (bias ± random error) and are presented in Figure 12.

For the high HLa concentration measurements, the correlation coefficient of the absolute differences between the two methods (Fluorimeter-YSI) and their individual means (HLa; $mmol \cdot l^{-1}$) showed that the measurement error was multiplicative ($r= 0.27$; $P= 0.62$). These results are shown in Appendix C (Figure 9). The calculated LOA for the 95% C.I. were 0.02 ± 0.02 $mmol \cdot l^{-1}$ (bias ± random error) and are presented in Figure 13. The antilogs of these values showed that the LOA on the ratio scale were 1.02 ± 1.02.

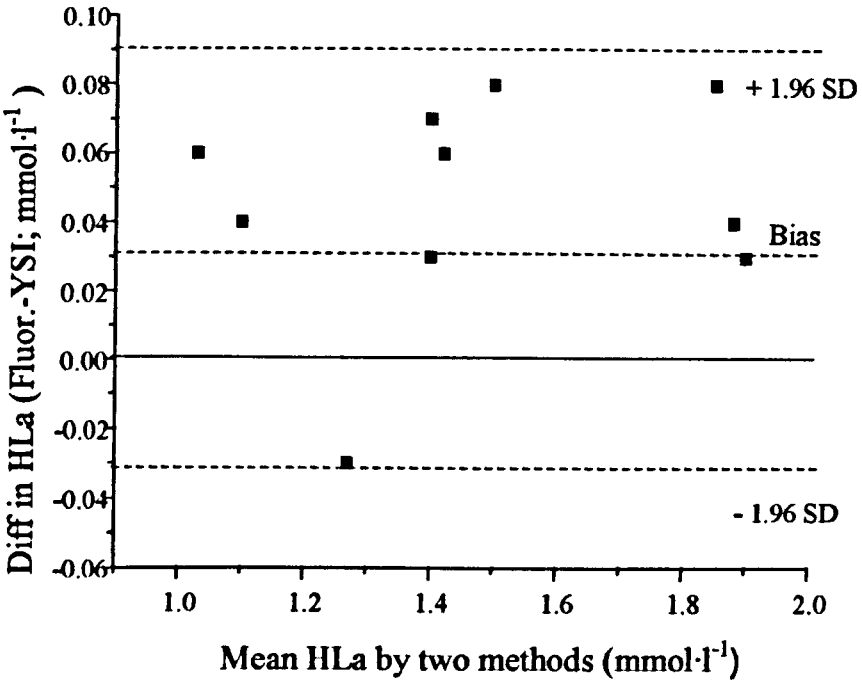


Figure 11. A Bland and Altman plot of the differences in low concentration of lactate (HLa; mmol·l^{-1}) between two methods (Fluorimeter-YSI) and their individual means (HLa; mmol·l^{-1}). The LOA (95% C.I.; dashed lines) are shown as bias ± random error (0.03 ± 0.06). The straight line indicates the zero line.

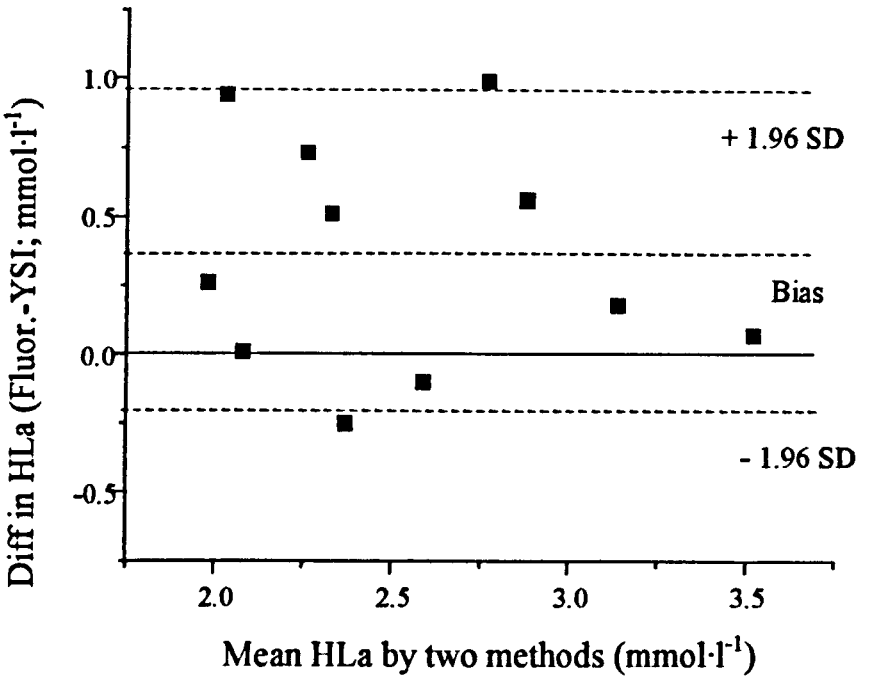


Figure 12. A Bland and Altman plot of the differences in medium concentration of lactate (HLa; mmol·l^{-1}) between two methods (Fluorimeter-YSI) and their individual means (HLa; mmol·l^{-1}). The LOA (95% C.I.; dashed lines) are shown as bias ± random error (0.4 ± 0.6 mmol·l^{-1}). The straight line indicates the zero line.

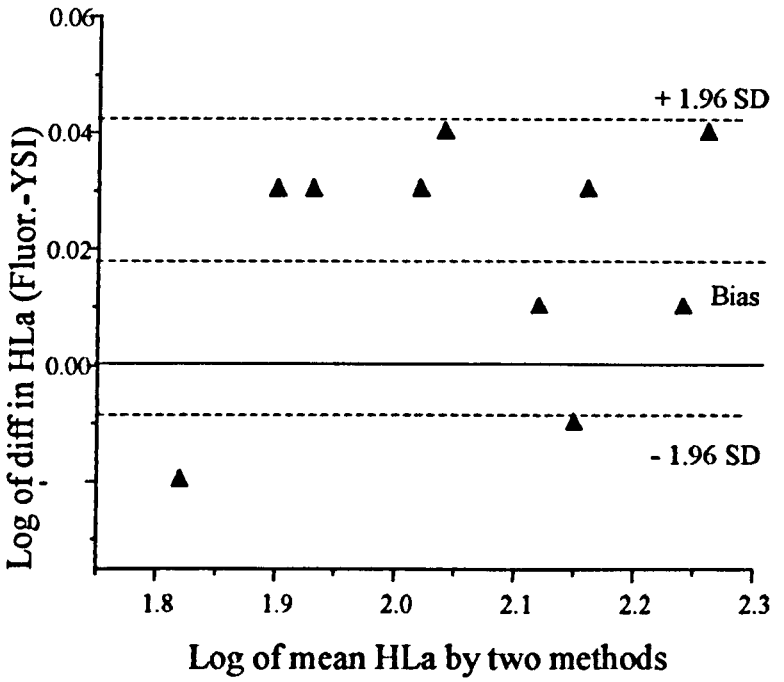


Figure 13. A Bland and Altman plot of the log transformed differences in high concentration of lactate (HLa) between two methods (Fluorimeter-YSI) and their individual means. The LOA (95% C.I.; dashed lines) are shown as bias ± random error (0.02 ± 0.02). The straight line indicates the zero line.

2.7.6.f. Discussion

The findings of this study demonstrated that the YSI is a valid method for measuring blood lactate (HLa) across different levels of HLa concentration. The LOA values for low, medium and high HLa concentrations (0.03 ± 0.06, 0.4 ± 0.6 mmol·l^{-1} and ratio 1.02 ± 1.02, respectively) were narrow and this indicates that there is good agreement between the readings of the YSI and the criterion method (Fluorimeter). These LOA compare favourably with those of a previous study on HLa concentration of critically ill patients (-0.65 ± 0.98 mmol·l^{-1}; Noordally and Vincent, 1999).

Bishop et al. (1992) postulated that analysis of lactate concentrations with the YSI has become very popular in 'sports science', but suggested that the validity of this equipment can be significantly improved through use of a lysing agent (Triton X-100). However, there have not been many studies that have examined the validity of this equipment, especially using LOA. Alternatively, there have been a few studies that have used the YSI as the criterion method in validation studies of other blood lactate analysis equipment. Such studies have validated the use of the Biosen 5030 (Davison et al., 2000) and the Chiron M865 (Noordally and Vincent, 1999) blood lactate analysers. The findings of the present study justify the use of the YSI as the criterion method in these studies.

CHAPTER 3

LACTATE AND CARDIOPULMONARY RESPONSES TO DRY-LAND ARM-PULLING AND LEG-KICKING IN COLLEGIATE AND RECREATIONAL SWIMMERS

This chapter presents the first of the three component studies in this thesis. The usefulness of dry-land ergometry in assessment of physiological responses to arm-pulling and leg-kicking exercise in swimmers of different training status is considered. A review of literature on previous studies that have assessed the responses to arm and leg exercise in other sports and in swimming is given in the introduction section. A description of the different equipment and exercise protocols used to assess the responses to arm and leg exercise in this study is presented in the methods and the findings are given in the results. Finally, in the discussion section the findings of this study are compared to those of previous studies and the usefulness of dry-land ergometry to assess physiological responses to arm and leg exercise in swimmers of different training status is discussed. This study has been published in: Konstantaki M., Swaine I.L.: Lactate and cardiopulmonary responses to simulated arm-pulling and leg-kicking in collegiate and recreational swimmers. *International Journal of Sports Medicine*, **20:** 118-121, 1999.

3.1. Introduction

There is little evidence of the ways in which the metabolic responses to arm-pulling and leg-kicking exercise in competitive swimmers differ when compared to those swimmers of lower training status. The lactate responses to swimming have been assessed using water-based testing (Maglischo and Bishop, 1982; Sharp et al., 1984; Robergs et al., 1990), but these studies have investigated the responses to whole-body free swimming. There have been a few studies that have demonstrated the differences in the energy costs (Adrian et al., 1966; Holmér, 1974) and the lactate concentration (Meyer et al., 1988) of the arm stroke and the leg kick, but these findings were related to swimming speed.

Assessments of arm and leg responses to exercise have previously employed arm-cranking and cycling (Reybrouck et al., 1975) and also free swimming (Adrian et al., 1966), but have not been used to assess swimmers of different training status. Rather, the changes due to training in the whole–body lactate metabolism have been investigated in competitive swimming (Denis et al., 1984). However, these studies have related the changes in metabolism to swimming speed. Also, the differences in the metabolism of the arms or the legs according to training status were not reported. This is especially the case for leg metabolism, which has not been assessed due to absence of appropriate ergometers.

The swim bench has been used as an alternative to water-based testing to assess arm power of swimmers (Armstrong and Davies, 1981; Sharp et al., 1982; Swaine and Reilly, 1983; Roberts et al., 1991; Obert et al., 1992; Johnson et al., 1993). It has also been used to assess cardiopulmonary responses to arm-pulling (Swaine and Zanker, 1996). This machine had been criticised due to the absence of leg-kicking. Recently, a new ergometer, which allows assessment of the front-crawl leg-kicking action has been developed. The additional leg-kicking ergometer has been used in conjunction with the swim bench to determine cardiopulmonary responses to arm-pulling and leg-kicking in competitive swimmers (Swaine, 1997). However, the lactate and cardiopulmonary

responses to arm-pulling and leg-kicking exercise in swimmers of different training status have not been investigated.

One of the main advantages of dry-land ergometry is that the physiological responses can be related to exercise intensity, rather than to other indices of water-based testing, such as resultant propulsion (Hollander et al., 1986). This way, the confounding influence of stroke technique that arises from water-based measurements is partly circumvented. This type of dry-land ergometry might allow comparisons of the metabolism of the upper and lower body segments in athletes with different training abilities. Such assessments could provide insight into the importance of upper- or lower- body conditioning for competitive swimmers. Therefore, the purpose of this study was to investigate the usefulness of dry-land ergometry in assessing the differences in lactate and cardiopulmonary responses to arm-pulling and leg-kicking in collegiate and recreational swimmers.

3.2. Methods

3.2.1. Subjects

Sixteen male aquatic athletes [9 swimmers; SW (mean age: 21 ± 4 years, stature: 1.83 ± 0.1 m, body mass: 81 ± 10 kg) and 7 recreational swimmers; RSW (mean age: 24 ± 2 years, stature: 1.86 ± 0.04 m, body mass: 82 ± 7 kg) gave written consent and were recruited to the study. There was no significant difference in body mass between the two groups (P=0.4). All SW were college swimmers who engaged in 1.5 hours of training 3-4 times per week. Their training distances were monitored every week for a period of two months before the study. These were (mean ± SD) 12000 ± 2500 metres. The RSW subjects were college students that participated in rugby and running. These athletes trained on average twice a week in their main sport and completed one or two swimming sessions per week (approximate duration: 45 minutes to 1 hour). Their weekly swimming training distances were (mean ± SD) 3000 ± 1000 metres.

3.2.2. Ergometers

The operation and calibration of the arm-pulling and leg-kicking ergometers has been detailed previously (Swaine and Zanker, 1996; Swaine, 1997) and has been described in Chapter 2 of this thesis. The arm-pulling ergometer used a computer interfaced isokinetic swim bench (Euroleader UK, Ltd., Gwent, UK). The leg-kicking ergometer was an adaptation of the swim bench unit, which used a device within which the swimmers placed their feet to simulate the front crawl leg-kicking action (University of Warwick, Warwick, UK).

3.2.3. Blood lactate analysis equipment

Blood lactate analysis was performed using an automated lactate analyser (Yellow Springs International, Ohio, USA). Lancet pin-prick capillary blood samples were taken from each subject's earlobe by use of micro-haematocrit tubes and pipetted into heparinised cuvettes. The samples were immediately refrigerated and analysed for their lactate concentration within 30 minutes of test completion.

3.2.4. Gas analysis equipment

Expired gases were analysed for their oxygen consumption using direct gas analysis equipment (COVOX Microlab, Exeter, UK), which consisted of an inspired air pneumotachograph and infra-red oxygen and carbon dioxide analysers (Servomex Ltd., Sussex, UK). The operation and calibration procedures of this equipment have been described in detail in Chapter 2. Calibration of the equipment was performed prior to testing using nitrogen (0% CO_2, 0% O_2) and span (4.98% CO_2, 21.72% O_2) calibration gases. Expired gases were mixed in a 3-litre chamber and were sampled at 30-second intervals. Oxygen consumption was sampled every 30 seconds and recorded every two minutes as the average of four 30-second values and at exhaustion.

3.2.5. The exercise tests

These comprised incremental arm-pulling (Plate 12) and leg-kicking (Plate 13) to volitional exhaustion. Maximal pull velocity (MPV) was set constant at 2.66 $m \cdot s^{-1}$ for both tests. All subjects visited the laboratory on three separate occasions. On their first visit, they familiarised themselves with the equipment and testing procedures by performing trials of the arm-pulling and the leg-kicking test. No data were collected during the trial tests. The second and third visits occurred at least three days apart to avoid any residual fatigue from previous testing. On these visits, the subjects performed either the arm-pulling or the leg-kicking test. The order of the tests was randomised to occur in alternating order to avoid any possible learning effects (Russell et al., 1992).

The subjects began arm-pulling or leg-kicking at 20 W for 1 minute and then the intensity of exercise increased by 10 $W \cdot min^{-1}$ for every minute thereafter (Fast Ramp protocol). The test was designed so as not to exceed 15 minutes in duration to eliminate local muscle fatigue (Yoshida, 1984). The first 2 minutes of the test were regarded as warm-up and were excluded from the measurements. Blood samples were taken every minute immediately after a change in exercise intensity (i.e. sampling at 65 W to reflect the lactate concentration at 60 W) and within 3 minutes from the termination of the test to determine the highest lactate concentration (HLa_{peak}). The tests were terminated either at voluntary exhaustion or when the subjects failed to keep up with the increasing power output by exercising at 10 W below the 'target power' for more than 1 minute.

3.2.6. Determination of the exercise intensity corresponding to 4 $mmol \cdot l^{-1}$ blood lactate concentration.

To determine the exercise intensity (Watts) that coincided with a blood lactate concentration of 4 $mmol \cdot l^{-1}$ (EI_{4mM}), the blood lactate values obtained for every minute of the exercise tests were plotted against increasing exercise intensities. A line was extended from the 4 $mmol \cdot l^{-1}$ point on the abscissa to the data set and then a line was interpolated to the corresponding exercise intensity value on the ordinate (Figure 14).

The same procedure was followed to determine the EI_{4mM} for each subject during the arm-pulling and the leg-kicking tests. An average EI_{4mM} value was computed for each of the tests for the collegiate and recreational swimmers, respectively. The method of interpolation has been previously used by Madsen and Lohberg (1987) and by Konstantaki et al., (1998).

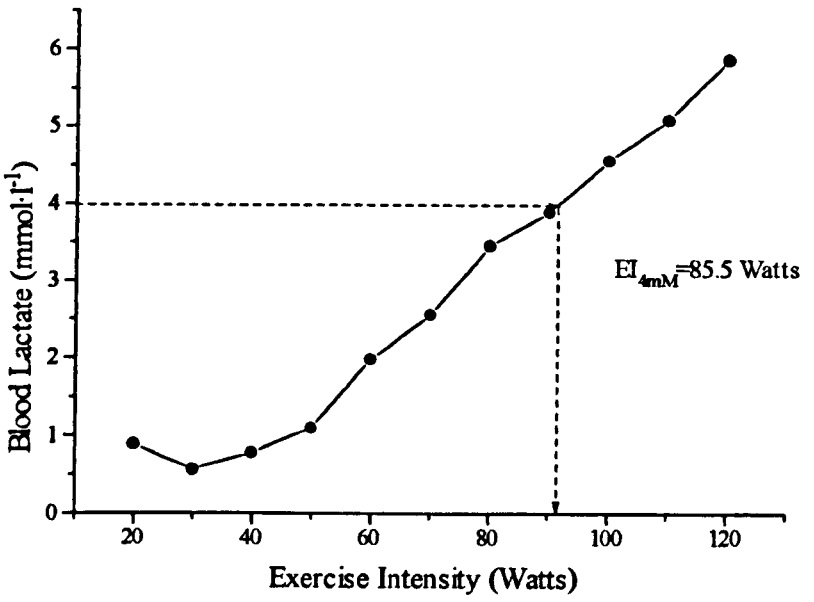


Figure 14. An example of the determination of EI_{4mM} for one subject.

3.2.7. Statistical Analysis

Multivariate analysis of variance (MANOVA) with discriminant analysis was used to assess the differences in HLa_{peak}, $\dot{V}O_{2peak}$, EI_{peak} and EI_{4mM} between the two groups. These differences were assessed for both arm-pulling and leg-kicking. The level of significance was set at $P<0.05$. The relationships between lactate concentration, oxygen consumption and exercise intensity for arm-pulling versus leg-kicking were also explored.

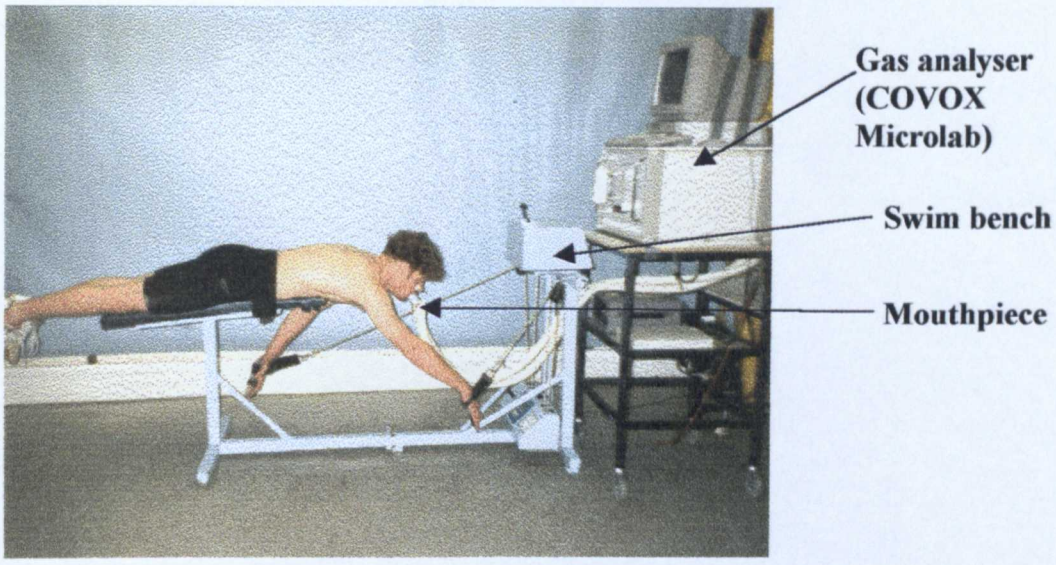


Plate 12. The arm-pulling test showing the swim bench, gas analyser and mouthpiece.

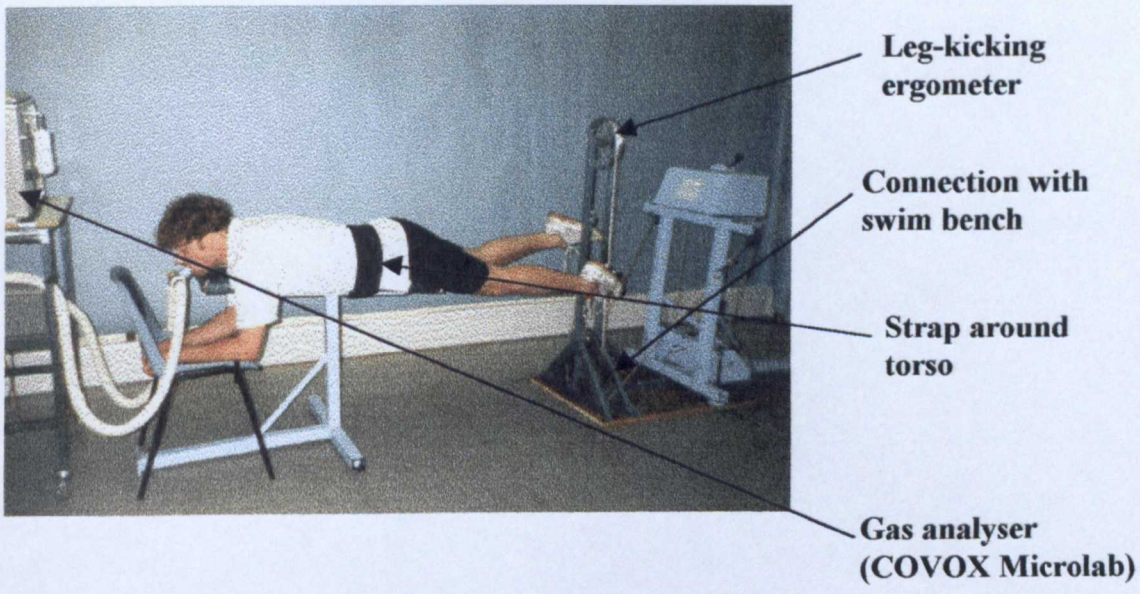


Plate 13. The leg-kicking test showing the leg-kicking ergometer, gas analyser and the strap used to secure the swimmer on the bench.

3.3. Results

For arm-pulling, the mean (± S.E.M) values showed that SW had higher EI_{4mM} (P=0.02) and EI_{peak} (114 ± 6 W vs 90 ± 4 W, P<0.05), but lower HLa_{peak} (P=0.03) than RSW. For leg-kicking, none of the responses differed. $\dot{V}O_{2peak}$ and $\dot{V}O_2$ at submaximal work loads ($\dot{V}O_2$-60, $\dot{V}O_2$-80) did not differ between the two groups for either arm-pulling ($\dot{V}O_{2peak}$: 3.1 ± 0.2 vs 2.8 ± 0.1 l·min^{-1}, F (1,14)=0.26; $\dot{V}O_2$-60: 1.58 ± 0.3 vs 1.68 ± 0.34 l·min^{-1}, F (1,14)=0.37; $\dot{V}O_2$-80; 2.04 ± .04 vs 2.11 ± 0.2 l·min^{-1}, F (1,14)=0.15, all P>0.05) or leg-kicking ($\dot{V}O_{2peak}$; 3.9 ± 0.1 vs 4.1 ± 0.1 l·min^{-1}, F (1,14)=3.15; $\dot{V}O_2$-60; 2.16 ± 0.2 vs 1.91 ± 0.19 l·min^{-1}, F (1,14)=2.62; $\dot{V}O_2$-80; 2.62 ± 0.2 vs 2.57 ± 0.19 l·min^{-1}, F (1,14)=2.81, all P>0.05). SW had higher arm-pulling to leg-kicking ratios for $\dot{V}O_{2peak}$ and EI_{4mM} than RSW. Also, SW had lower RER values at submaximal intensities (RER_{60}, RER_{80}) than RSW, but these differences were only noted for arm-pulling (R_{60}: 0.94 ± 0.04 vs 1.01 ± 0.1, F (1,14)=5.13; R_{80}: 1.00 ± 0.06 vs 1.14 ± 0.1, F (1,14)=6.45, all P<0.05) Significant differences were identified for $\dot{V}O_{2peak}$, HLa_{peak} and EI_{4mM} (F (1,14)=6.3, 7.2, and 8.2, respectively, all P<0.05) arm:leg ratios in SW. The HLa_{peak}, EI_{4mM}, $\dot{V}O_{2peak}$ values and the arm:leg ratios are given in Table 8. The mean exercise intensity at a blood lactate concentration of 4 mmol·l^{-1} in response to arm-pulling versus leg-kicking in SW and RSW is shown in Figure 15.

Table 8. Mean (± S.E.M.) for HLa_{peak}, EI_{4mM} and $\dot{V}O_{2peak}$ responses to arm-pulling vs leg-kicking (SW, n=9; RSW, n=7; * significant at $P<0.05$).

	ARMS			**LEGS**			**ARM:LEG RATIO**		
	HLa_{peak} ($mmol \cdot l^{-1}$)	EI_{4Mm} (W)	$\dot{V}O_{2peak}$ ($l \cdot min^{-1}$)	HLa_{peak} ($mmol \cdot l^{-1}$)	EI_{4mM} (W)	$\dot{V}O_{2peak}$ ($l \cdot min^{-1}$)	HLa_{peak} (%)	EI_{4mM} (%)	$\dot{V}O_{2peak}$ (%)
SW	6.7±0.2	94±6.0*	3.1±0.1	5.2±0.5	86±7.0	3.4±0.1	129±3*	109±8*	91±6*
RSW	7.4±0.3*	70±6.3	2.8±0.1	6.3±0.7	78±3.2	4.1±0.1	117±5	90±7	68±4

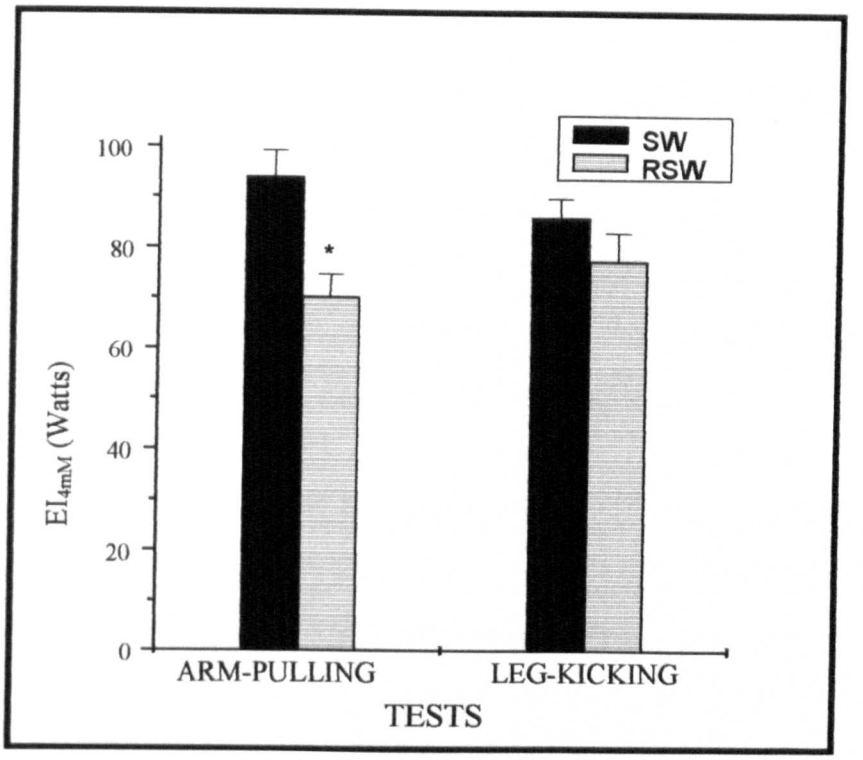


Figure 15. Mean exercise intensity (Watts) at a blood lactate concentration of 4 mmol·l^{-1} (EI_{4mM}) in response to dry-land arm-pulling versus leg-kicking in collegiate (SW) and recreational swimmers (RSW). Error bars are S.E.M. * Significant at $P<0.05$.

3.4. Discussion

Previous investigations have related the lactate responses to either whole-body swimming (Maglischo and Bishop, 1982; Harrison et al., 1992) or arm stroking and leg kicking (Meyer et al., 1988) to swimming speed, whereas the lactate responses in this study were related to exercise intensity. Therefore, no direct comparison can be made between the findings of those studies and the present study. In this study, it was shown that recreational swimmers achieved higher HLa_{peak} during arm-pulling than collegiate swimmers. One would expect that trained swimmers would be able to sustain higher lactates before the onset of fatigue. Swaine and Reilly (1983) suggested that the posture adopted on the swim bench restricts chest expansion, thereby limiting ventilation. Therefore, the collegiate swimmers in this study might have stopped exercising due to breathing restrictions and not due to blood lactate accumulation.

The higher EI_{4mM} and EI_{peak} values for arm-pulling in the collegiate swimmers in this study suggest that the distinguishing factor between swimmers of different training status is the degree of conditioning in their arms. Even though the volume of swimming training in the collegiate swimmers was low, it seems it was enough to elicit specific muscular adaptations (Sawka, 1986). It is not clear from the data in this study whether the differences observed between the two groups were due to increased muscle mass or increased muscle oxidative capacity due to training (Holloszy and Coyle, 1984). However, similar differences between the groups were not noted for leg-kicking. The recreational swimmers in this study participated in sports that involved predominantly leg exercise (i.e. rugby and running). Thus, they probably had a well-developed muscle oxidative capacity, which might have allowed them to sustain high exercise intensities during leg-kicking. Alternatively, it is likely that the findings in this study might have been different had we used recreational swimmers who exercised their upper body (e.g. kayakists).

A combined assessment of lactate and cardiopulmonary variables can better enhance our understanding of endurance performance (Clausen et al., 1970; Denis et al., 1984; Allen

et al., 1985). Although the $\dot{V}O_{2peak}$, $\dot{V}O_2$-60 and $\dot{V}O_2$-80 responses to arm-pulling versus leg-kicking were not different between the groups in this study, these values compare favourably with those reported previously in swimmers for either tethered or flume swimming (Bonen et al., 1980; Maglischo et al., 1980) and dry-land ergometry (Swaine and Zanker, 1996). These results illustrate that the groups were not different in dry-land movement economy.

Arm metabolism showed enhancement in collegiate swimmers in this study. Although no direct measurements of metabolism, such as muscle enzymes were made, it was possible to estimate the metabolic demands of arm-pulling and leg-kicking by using the respiratory exchange ratio (RER). At submaximal intensities collegiate swimmers had lower R-values for arm-pulling than recreational swimmers. The same difference was not observed for leg-kicking. Again, this might be the result of the lower limb predominance in the recreational swimmers in this study due to competitive training in sports that engage primarily the lower body muscle groups.

The $\dot{V}O_{2peak}$ arm:leg ratio of 68% observed for the recreational swimmers in this study agrees closely with the 63% and 70% values found by Reybrouck et al. (1975) and Åstrand and Saltin (1961). It appears that the lower muscle mass in the arms is responsible for lower oxygen consumption values during arm exercise (Sawka, 1986; Zoladz et al., 1995). However, the $\dot{V}O_{2peak}$ arm:leg ratio of 91% found for the competitive swimmers has not been reported previously. These results suggest that competitive swimming training may enhance the oxidative capacity of both arms and legs in concert, rather than either the arms or legs.

The arm:leg ratios at EI_{4mM} for the collegiate (109 ± 8%) and the recreational swimmers (90 ± 7%) in this study contradict the values found by Reybrouck et al. (1975). They used arm-cranking and cycling and found an arm:leg ratio of 64%. Although they did not use swimmers or the same measure of 'anaerobic threshold', the differences are

striking. Some of the differences might be attributed to the different types of ergometry and the different types of subjects used (untrained versus trained). Nevertheless, it appears that the dry-land ergometry used in this study reflects the balance of arm and leg local muscle endurance associated with the training status of swimmers.

It was shown in this study that dry-land ergometry can be a useful tool in determinations of upper and lower body power output of swimmers. Such determinations might shed light into the different metabolic demands of the upper and lower body of swimmers. This approach could help swimming coaches to monitor the changes in the metabolism of the upper and lower body of their swimmers that may occur due to competitive swimming training. This type of ergometry might also be useful to sport physiologists who are interested in investigating the physiological responses to arm-pulling and leg-kicking exercise in relation to exercise intensity. Additionally, this type of dry-land ergometry provides a more familiar type of exercise for swimmers than other types of dry-land ergometry that have been used previously, such as arm-cranking and cycling ergometry.

CHAPTER 4

THE EFFECTS OF ARMS- VERSUS LEGS-ONLY SWIMMING TRAINING ON PERFORMANCE INDICES AND GAS EXCHANGE RESPONSES TO DRY-LAND ARM-PULLING AND LEG-KICKING IN SWIMMERS

This chapter discusses the effects of specialised swimming training on different indices of swimming performance and physiological responses to dry-land arm-pulling and leg-kicking in swimmers. A review of literature on previous studies that have assessed the effects of training in other sports and in swimming is given in the introduction. Also, the rationale for using dry-land ergometry to assess the effects of swim training is stated in the same section. A description of the different equipment and exercise protocols used in this study is presented in the methods and the findings are presented in the results section. Finally, the appropriateness of dry-land ergometry to assess the changes due to training in physiological measures is discussed.

This study was voted the best new contribution of a young investigator and was awarded the 'Archimedes' prize at the VII International Symposium of Biomechanics and Medicine in Swimming, which was held in Jyväskylä, Finland, in July 1998.

The findings of this study have been published: Konstantaki M, Winter EM, Swaine IL. The effects of arms- or legs-only training on indices of swimming performance and dry-land endurance in swimmers. In: Keskinen K, Komi P and Hollander P (eds), *Biomechanics and Medicine in Swimming VII.* Department of Biology of Physical Activity, University of Jyväskylä, Jyväskylä, Finland, pp. 391-395, 1999.

4.1. Introduction

The effects of arms- and legs-only training in swimmers are unclear. There are no published studies that have investigated the effects of such upper- and lower-body training upon oxygen uptake of the arms and legs and upon swimming performance. In other athletes, studies of the effects of training have mostly assessed oxygen uptake and gas exchange indices, such as ventilatory threshold (VT; Davis et al., 1976). The VT has been used as a non-invasive marker of the anaerobic threshold (Reinhardt et al., 1979) in attempts to explain running (Farrel et al., 1976), cycling (Powers et al., 1979) and swimming performance (Swaine, 1994). However, there have not been any similar studies conducted on swimmers, especially using comprehensive assessments of cardiopulmonary responses to arm and leg exercise.

Of course, improvements in oxygen uptake ($\dot{V}O_2$) are best demonstrated, when similarity exists between the exercise test and the specific mode of training (Strømme et al., 1977). Generally, 'specificity of training' has been demonstrated using arm and leg exercise (Clausen et al., 1973), two-legged (Pechar *et al.*, 1974) and one-legged (Saltin et al., 1976) cycling, arm-cranking (Bar-Or and Zwiren, 1975) and running (McArdle et al., 1978), but these studies offer little explanation of the effects of arms- and legs-only swimming training. There have been evaluations of the effects of arm training on aerobic power in swimmers that have used tethered swimming (Magel et al., 1974), flume swimming (Bonen et al., 1980) and swim bench protocols (Gergley et al., 1984). The effects of legs-only training in swimmers have been mostly overlooked.

Studies of oxygen uptake ($\dot{V}O_2$) and ventilatory threshold (VT) responses to arm and leg exercise in swimmers have been hindered by a lack of methods by which VT can be assessed. For this, small increases in exercise intensity are required. Also, when comparing ventilatory threshold responses to arm and leg exercise, it is necessary to have common exercise intensities for both arm and leg exercise. In methods like those involved in the swimming flume (Åstrand and Englesson, 1971), the arm and

leg exercise intensities seldom overlap. Recently, dry-land methods of assessment have been used to assess the $\dot{V}O_2$ responses to arm exercise (Meerloo et al., 1987) and a leg-kicking ergometer has been developed that allows comparison of the $\dot{V}O_2$ responses to arm and leg exercise in swimmers (Swaine, 1997). This leg-kicking ergometer has been used in conjunction with the swim bench to assess lactate and cardiopulmonary responses to incremental arm-pulling and leg-kicking exercise in collegiate and recreational swimmers (Konstantaki and Swaine, 1999).

Performance in middle-distance front crawl swimming depends largely upon two main factors. These are aerobic power and swimming technique (Toussaint and Beek, 1992). In the past, attempts to explain swimming performance have concentrated mainly upon whole-body performance. Few researchers have investigated the separate contributions of arm-pulling and leg-kicking. Most studies have assessed maximum oxygen consumption ($\dot{V}O_{2max}$) during swimming (Dixon and Faulkner, 1971) using equipment, such as the swimming flume (Holmér et al., 1974; Bonen et al., 1980) and tethered swimming (LePére and Porter, 1975). However, oxygen consumption of the upper or lower body whilst swimming was not assessed in any of these studies.

Swimming technique has been investigated in only a few studies, but the separate arm-pulling and leg-kicking technique has not been assessed in the same study. Propulsion in front crawl swimming is primarily affected by arm technique (Hay, 1986). Indeed, it has been postulated that leg exercise in swimming is only used to compensate for the negative buoyancy of the legs (Bucher, 1974; Hollander et al., 1988). In view of this, several workers have focused upon studying only the arm stroke (Ogita and Tabata, 1993; Ogita and Taniguchi, 1995; Wakayoshi et al., 1995). Swimming technique has been assessed simply using a stroke index (Craig and Pendergast, 1979; Craig et al., 1985; Arellano and Pardillo, 1992). There have been

no studies of the arm-pulling and leg-kicking stroke indices in relation to arms- or legs-only swimming performance in swimmers.

Assessments of the effects of arms- or legs-only swimming training on the arms- or legs-only swimming performance indices, $\dot{V}O_2$ and ventilatory threshold responses to dry-land arm-pulling and leg-kicking might help sport physiologists to identify the differences or similarities in the physiological adaptations of the upper and lower body of swimmers. These assessments might also provide insight into the relative contributions of upper and lower body adaptations to overall training effects of whole body exercise. The purpose of this study was to investigate the usefulness of dry-land ergometry in assessing changes in physiological responses to arm-pulling and leg-kicking exercise due to arms- and legs-only swimming training.

4.2. Methods

4.2.1. Subjects

Eight male (mean ± SD; age 17 ± 4 years, stature 1.75 ± 0.09 m and body mass 66 ± 11 kg) and six female (mean ± SD; age 15 ± 5 years, stature 1.65 ± 0.05 m and body mass 60 ± 7 kg) club swimmers provided written informed consent and were recruited to the study. All subjects were competitive swimmers who engaged in training for 1.5 hours at least five times per week for the period of four months preceding the study. Their training experience varied from four to ten years and they were all members of the same swimming club (400 m time: 309 ± 25 seconds). Training distances were recorded for a period of two months preceding the study and averaged 20.000 ± 2500 m per week. Isolated arm or leg swimming training was recorded for a month prior to the study. Arms-only training averaged 6 ± 2% (20-25 minutes per week), whereas legs-only training averaged 4 ± 2% (15-20 minutes) of the weekly training time (450 minutes: 5 sessions of approximately 90 minutes each). This programme included arm or leg training for all strokes.

4.2.2. The Training Programme

The training programme was six weeks in duration and comprised 20% of the total weekly training time (33% of the training time within three training sessions per week) being devoted to arm-pulling or leg-kicking front crawl swimming exercises. This amounted to approximately 30 minutes in a 90-minute session (3 x 30 minutes: 90 min·wk^{-1}) and corresponded to an additional 14% and 16% for arms- and legs-only weekly swimming training, respectively, when compared to pre-training conditions. The participants were divided into two groups; one group, assigned to arm-pulling exercises (ARMS) and a second group, assigned to leg-kicking exercises (LEGS). The groups were randomly assigned, but by chance male and female participants were evenly distributed among the two groups (4 males and 3 females per group). The training programme took place three times per week in the beginning of each training session immediately after the warm-up. It mainly comprised of arm-pulling or leg-kicking drills using training aids such as, paddles and pull-buoys for arm-pulling and kick boards or fins for leg-kicking. Approximately 700-1000 metres were covered by arm or leg training alone within any given training session. The training sets consisted primarily of moderate intensity swimming designed to produce heart rate responses between 130-170 beats·min^{-1}. The swimming training was carried out in a 30-metre (33-yard) swimming pool. The training sets included repeated distances of 60 metres, 90 metres, 120 metres and 150 metres. Resting intervals ranged between 15-25 seconds between bouts (work to rest ratio of 2:1).

4.2.3. Ergometers

The calibration and use of the arm-pulling (Euroleader UK Ltd., UK) and the leg-kicking ergometer (University of Warwick, Warwick, UK) have been described in detail previously (Swaine and Zanker, 1996; Swaine, 1997). The arm-pulling ergometer comprised a computer-interfaced swim bench, where the intensity of effort was dictated through software (H.K.Smith, University of Sunderland). The leg-kicking ergometer is an adaptation of the swim bench and used a device within which

the swimmers placed their feet to simulate the front crawl leg-kicking action. This ergometer was connected to the swim bench interface unit and the exercise intensity was dictated in the same way as when using the arm-pulling ergometer.

4.2.4. Measurement of oxygen uptake and carbon dioxide output

Expired gases were analysed for their oxygen uptake and carbon dioxide output using on-line gas analysis equipment (COVOX Microlab, Exeter, UK). This comprised paramagnetic oxygen and infra-red carbon dioxide analysers (Servomex Ltd., Sussex, UK) and a pneumotachograph. Calibration of this equipment was performed prior to and after every testing session, using nitrogen and a gas of known concentration (4.95% CO_2, 15% + 21.5% O_2; BOC Gases Ltd., Surrey, U.K.). The reason for using two different concentration calibration gases to calibrate O_2 was to span the operating range. The aim of this method was to perform calibration above and below the expected O_2 values. A detailed description of the operation and calibration procedures of the COVOX Microlab has been presented in Chapter 2 of this thesis. Expired gases were mixed in a three-litre chamber and sampled at 15-second intervals. There were no single values for a specific time point, but mixing chamber data were sampled every 15 seconds. Oxygen uptake and carbon dioxide output were recorded every 30 seconds (as an average of two 15-second values) and at exhaustion.

The reproducibility of the gas analysis equipment was assessed in a separate study that took place before the main testing. Therein, five swimmers were asked to perform two arm-pulling and two leg-kicking incremental exercise tests to exhaustion within 48 hours and the peak oxygen uptake ($\dot{V}O_{2peak}$) values were compared. No significant differences were found between the two arm-pulling ($r = 0.94$, Coefficient of Variation [CV]=3.53%, $P>0.05$) and the two leg-kicking tests ($r=0.96$, CV=2.87%, $P>0.05$).

4.2.5. Determination of ventilatory threshold

The method used for determination of ventilatory threshold (VT) was based on the method suggested by Fukuba et al. (1988). This method identified VT as the point at which there is a sudden systematic increase in the ventilatory equivalent for O_2 ($\dot{V}E/\dot{V}O_2$) was used to determine the VT during the arm-pulling and the leg-kicking tests in the ARMS and the LEGS groups before and after training. The values for $\dot{V}E/\dot{V}O_2$ were plotted against exercise intensity and the breakpoint at the beginning of the systematic increase in the ventilatory equivalent for O_2 was determined. To determine the exercise intensity which corresponded to the VT (VT_W), the graphical technique proposed by Swaine (1994) was used. This technique involved fitting two straight lines on the $\dot{V}E/\dot{V}O_2$ data (one before the VT and one after the VT). The point at which these two lines intersected was taken as the exact point of VT. From this point the exercise intensity that coincided with the VT was interpolated (Madsen and Lohberg, 1987). An example of this technique is shown in Figure 16.

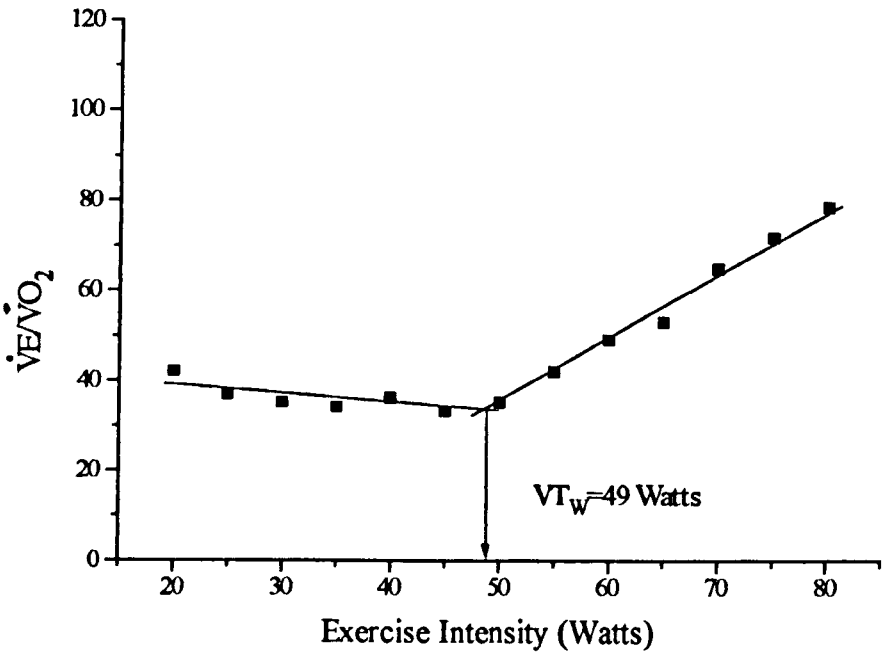


Figure 16. An example of the determination of the exercise intensity at ventilatory threshold (VT_W).

4.2.6. The dry-land tests

All participants performed two incremental exercise tests to exhaustion, using the arm-pulling and the leg-kicking ergometers. One test was performed on each ergometer. Maximal pull velocity (MPV) was set constant at 2.66 $m \cdot s^{-1}$ and at 2.74 $m \cdot s^{-1}$ to allow optimal stroke rates at higher and lower resistance for males and females, respectively (Swaine and Zanker, 1996). All participants visited the laboratory on three separate occasions. On their first visit, subjects were allowed to accustomise to the arm-pulling and leg-kicking ergometers by performing short duration trial tests. No data were collected during these tests. The second and third visits were immediately prior to and after the six-week swimming training programme, when subjects again performed an arm- pulling and a leg-kicking test.

One hour of recovery was allowed between tests. The order of the tests on both occasions was balanced to minimise any possible learning effects (Russell et al., 1992).

4.2.7. The arm-pulling and leg-kicking tests

The participants began arm-pulling and leg-kicking at various exercise intensities depending on age and gender. Males over 17 years started arm-pulling at 40 W, whereas those less than 17 and all females started at 30 W. All swimmers began leg-kicking at 20 W. The exercise intensity for both tests was set to increase by 7.5 $W \cdot min^{-1}$. The test was designed so as not to exceed 15 minutes in duration to eliminate local muscle fatigue (Yoshida, 1984). The first two minutes of the test were regarded as a warm-up period. All subjects breathed via a mouthpiece throughout the exercise tests to allow collection of expired gases (see Plates 12 and 13 on page 146). The tests were terminated when the subjects failed to maintain exercise intensity within ± 20 W of the target power output. Dry-land endurance was measured as total exercise time (TET_{ARMS} and TET_{LEGS}).

4.2.8. The swimming tests

All swimmers performed an arms- and a legs-only and a full stroke front crawl swimming tests before and after the 6-week swimming training programme. The testing was performed on three occasions two days apart. All tests were performed at maximum effort in a 31-metre (33-yard) swimming pool. On all occasions, testing took place in the beginning of the training session immediately after the warm-up. The individual times for each test were recorded. For the arms-only test, the swimmers were asked to cover six lengths of the swimming pool (200 metres) using only the front crawl pulling action. To keep their legs afloat and minimise drag, the swimmers used a pull-buoy, whereas their ankles were fastened with an elastic band. For the legs-only test, the swimmers covered six lengths of the swimming pool (200 metres) using only the front crawl leg-kicking action. A standard kick board was

used to support the swimmers' upper body during kicking. The full stroke test employed the front crawl stroke performed by arms and legs in a synchronous action. The order of the tests was randomised to avoid any learning effects. A video camera was placed on the pool side at an appropriate distance and was set to record the swimmers' movements throughout the arms- and legs-only tests. These video recordings were later used to calculate distance per pull (DPP) and distance per kick (DPK) during the arms- and legs-only tests. To calculate distance per pull, the number of arm pulls performed per length were first counted. The number of arm pulls was then divided by the distance of the pool length (i.e. 20 strokes divided by 31 metres=0.6 metres). The sum of the distance per pull for all lengths was computed and then averaged by 6 (i.e. the number of lengths for the 200 m distance). This resulted in the calculation of the average DPP for each swimmer. The same procedure was followed to calculate the distance per kick with the only difference that the number of kicks were now counted.

4.2.9. Statistical analysis

A two-way Analysis of Variance (ANOVA; groups x time) with Repeated Measures on one factor (time) was employed to assess the differences in TET_{ARMS}, TET_{LEGS}, DPP, DPK, 200_{ARMS}, 200_{LEGS}, 400_{FULL}, $\dot{V}O_2$-60, $\dot{V}O_{2peak}$ and VT_W between the ARMS and LEGS groups and also between the different tests. Significance levels were set at $P<0.05$.

4.3. Results

In the ARMS group, TET_{ARMS} (25 ± 5%; P=0.01), 200_{ARMS} (13 ± 4%, P=0.03), DPP (7 ± 2%; P=0.01), $\dot{V}O_2$-60 (18 ± 2%; P=0.04) and VT_W (20 ± 3%; P=0.01) improved post-training. In this group there were no changes in TET_{LEGS} (P=0.6), 200_{LEGS} (P=0.09), DPK (P=0.2), 400_{FULL} (P=0.4) and $\dot{V}O_{2peak}$ (P=0.4). In the LEGS group, 200_{LEGS} (6 ± 2%; P=0.01), DPK (4 ± 1%; P=0.003), $\dot{V}O_2$-60 (20 ± 3%; P=0.02) and VT_W (37 ± 5%; P=0.01) were shown to improve in response to training. There were no changes in this group in TET_{LEGS} (P=0.3), TET_{ARMS} (P=0.7), 200_{ARMS} (P=0.1), 400_{full} (P=0.4) and $\dot{V}O_{2peak}$ (P=0.2). The mean ± S.E.M values for $\dot{V}O_{2peak}$, $\dot{V}O_2$-60, 200_{ARMS}, 200_{LEGS}, and 400_{FULL} in the ARMS and the LEGS groups are given in Table 9. The mean (± S.E.M) values for total exercise time and 200 m times (TET_{ARMS} and 200_{ARMS}, respectively) in swimmers who trained their arms (ARMS) before and after training are shown in Figure 17. The mean (± S.E.M) values for DPP and DPK before and after training in the ARMS and the LEGS groups respectively are displayed in Figure 18. The mean (± S.E.M) values for VT_W pre- and post-training in the ARMS and the LEGS groups are shown in Figure 19.

Table 9. Pre- and post-training $\dot{V}O_{2peak}$ ($l \cdot min^{-1}$) and $\dot{V}O_2$-60 ($l \cdot min^{-1}$) responses to arm-pulling and leg-kicking and swim times (s) for 200_{ARMS} 200_{LEGS} and 400_{FULL}, respectively in the arm-trained (ARMS) and leg-trained (LEGS) groups. Values are mean ± S.E.M. * Significant at $P< 0.05$.

	ARMS		**LEGS**	
	Pre-training	**Post-training**	**Pre-training**	**Post-training**
Arm $\dot{V}O_{2peak}$	1.89 ± 0.2	1.91 ± 0.1	2.36 ± 0.3	2.33 ± 0.3
Arm $\dot{V}O_2$-60	1.52 ± 0.2	1.24 ± 0.1*	2.06 ± 0.2	2.01 ± 0.2
Leg $\dot{V}O_{2peak}$	2.24 ± 0.2	2.29 ± 0.1	2.61 ± 0.4	2.59 ± 0.4
Leg $\dot{V}O_2$-60	2.08 ± 0.2	2.08 ± 0.1	2.01 ± 0.2	1.60 ± 0.1*
200_{ARMS}	187 ± 10.0	164 ± 6.0*	147 ± 3.0	145 ± 4.0
200_{LEGS}	233 ± 16.0	234 ± 20.0	223 ± 10.0	211 ± 10.0*
400_{FULL}	344 ± 17.0	340 ± 14.0	319 ± 11.0	308 ± 16.0

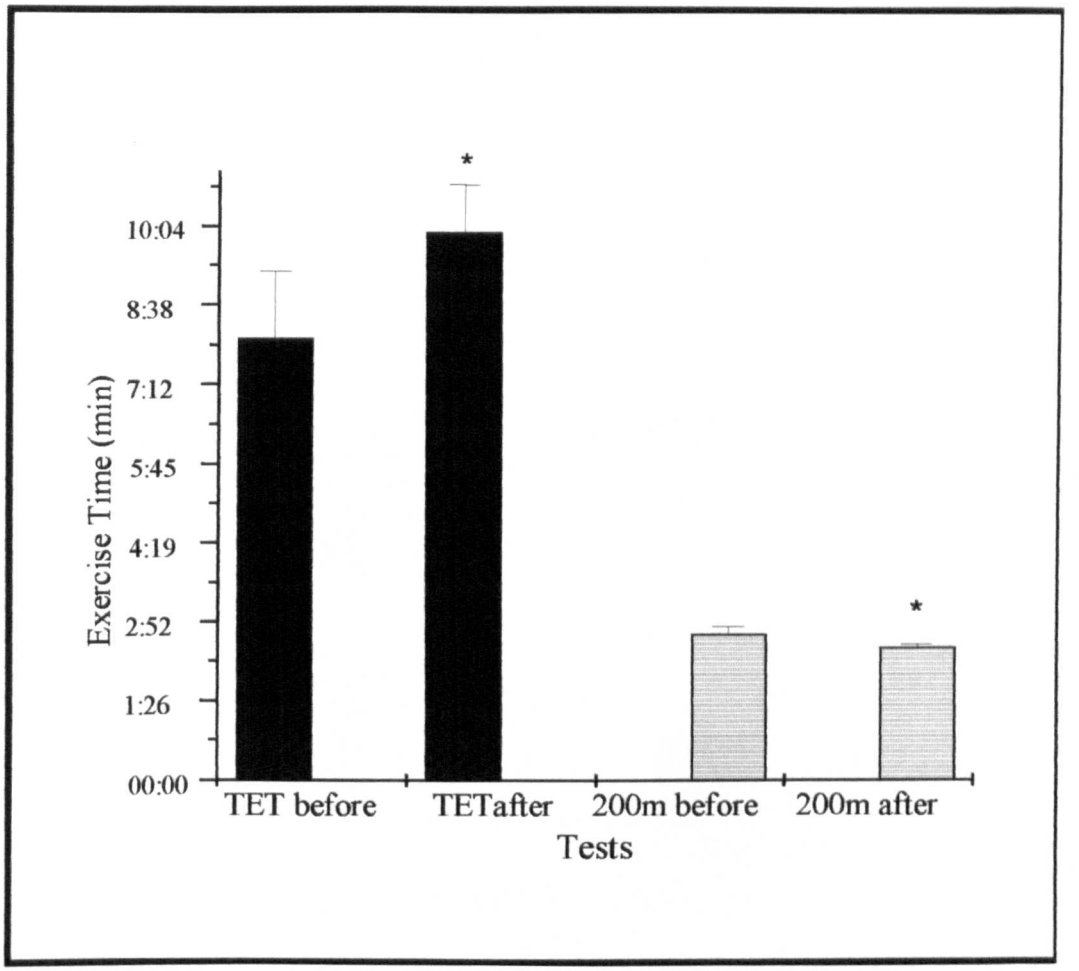


Figure 17. Mean total exercise time (minutes) and 200 m time in swimmers who trained their arms (ARMS; TET_{ARMS} and 200_{ARMS}, respectively) before and after training. Error bars are S.E.M. * Significant at $P<0.05$.

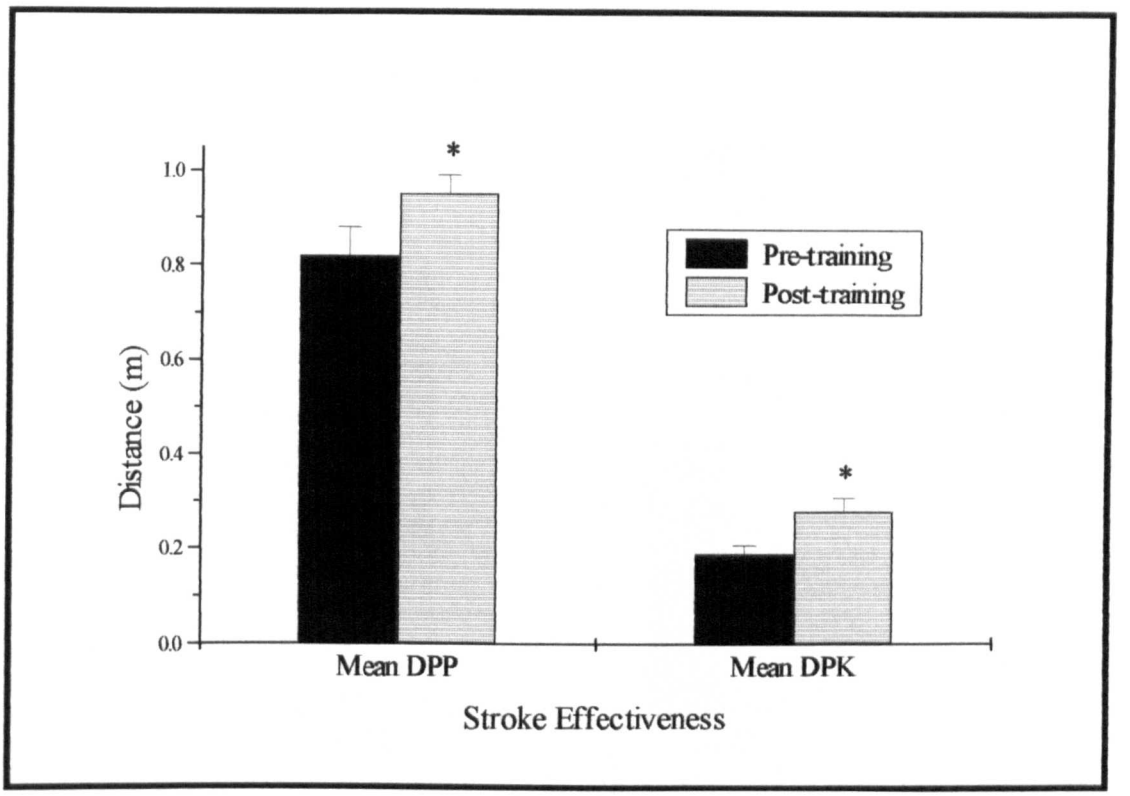


Figure 18. Mean distance per pull (DPP) in the ARMS group and mean distance per kick (DPK) in the LEGS group pre- and post-training. Error bars are S.E.M. *Significant at $P<0.05$.

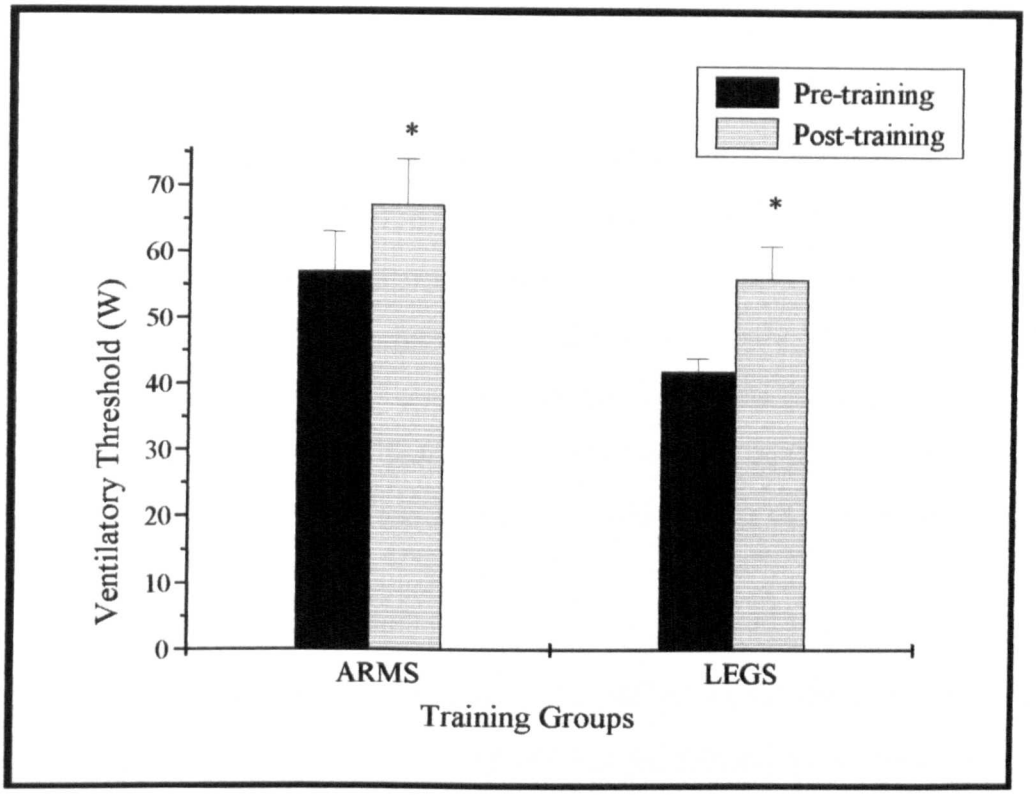


Figure 19. Mean exercise intensity at ventilatory threshold (VT_W) for arm-pulling and leg-kicking exercise pre-training and post-training in swimmers who trained their arms (ARMS) or their legs (LEGS). Error bars are S.E.M.
* Significant at $P<0.05$.

4.4. Discussion

This study demonstrates that arm or leg swimming training of 20% of the total weekly training time improves arms- or legs-only swim time, distance per pull and distance per kick for 200 metres, but not full stroke swim time for 400 metres. These changes were reflected in the dry-land measurements of reduced oxygen uptake at 60 W and enhanced ventilatory threshold, but no changes were noted for peak oxygen uptake ($\dot{V}O_{2peak}$). Studies that have demonstrated significant increases in $\dot{V}O_{2peak}$ following arm-cranking (Davis et al., 1987), cycling (Hardman et al., 1986) and also swimming (Rinehardt et al., 1992) training have used untrained subjects or recreational swimmers and thus, the changes in oxygen uptake could be attributed to the initial state of training. This study used competitive swimmers in whom the percentage of additional arms- (+14%) or legs-only (+16%) training might not have been adequate to induce training adaptations in peak oxygen uptake of the upper or lower body (Pollock et al., 1975).

In spite of the small training stimulus, the marked reduction in arm and leg oxygen uptake at 60 W ($\dot{V}O_2$-60) in the ARMS and the LEGS groups (-18 ± 2% and -20 ± 3%, respectively) could indicate enhanced motion economy in the trained segments, but confirmation of this would require measurements during free swimming (Toussaint, 1990). These findings are similar to those in runners and cyclists where improvements at given submaximal oxygen uptake values have been shown after training (Lieber et al., 1989; Foster et al., 1995). It also appears that the arms- and legs-only training, seemed to cause specific changes, since improvements in arm-pulling and leg-kicking $\dot{V}O_2$-60 were noted only in the trained segments. It appears that this amount of arms- or legs-only training did not elicit any unintended training adaptations in the non-trained segments as has been demonstrated in running (Foster et al., 1995).

Another notable result in our study was the increase in dry-land arm-pulling and leg-kicking power output at ventilatory threshold (VT_W; +20 ± 3% and +37 ± 5%, respectively). These results agree with previous findings (Clausen et al., 1973; Rasmussen et al., 1975), where a reduction in $\dot{V}E/\dot{V}O_2$ at given power outputs was observed only in the arm or leg muscle groups utilised in the arms- or legs-only training. The VT_W values for arm-pulling in the ARMS group were lower in our study when compared to those found by Swaine (1994; 100 ± 20 W versus 64 ± 5 W). This difference in power output can be attributed to the fact that some of the subjects in our study were female swimmers compared to solely male participants as used by Swaine (1994).

Dry-land endurance was reflected in total exercise time (TET) and was shown to increase in response to arms-only training (TET_{ARMS}). It has been postulated that work performance and aerobic power are enhanced when specific muscle groups are overloaded. This has been attributed to factors distal to the capillary that are specifically involved in the local training response (Ceretelli et al., 1979) and to facilitation of either oxygen transport or utilisation at the local level (Holloszy et al., 1984; Gregg et al., 1989). However, the same difference was not noted for leg dry-land endurance, even though a higher percentage (+2%) was devoted to legs-only training during the study compared to arms-only training (16% for legs and 14% for arms). It might be the case that legs are not as responsive to training adaptations, when compared to the arms. Consequently, a greater percentage of legs-only training might be required to increase leg endurance.

Another important finding was that the post-training times for 200 metres arms-only (200_{ARMS}) and 200 metres legs-only (200_{LEGS}) in the ARMS and LEGS groups respectively, were shown to decrease, when compared to the respective pre-training times. These results might illustrate an increased capacity of the trained muscles to generate ATP aerobically (Gollnick et al., 1972). Distance per pull in the ARMS (DPP) and distance per kick in the LEGS (DPK), increased post-training (10 ± 3%

and 5 ± 2%, respectively). Stroke effectiveness is closely related to swimming technique (Toussaint and Beek, 1992). It appears that arms- and legs-only-swimming training had a positive effect on the separate swimming technique of the arms and the legs in this study. These results agree with those of a previous where increases in distance per stroke were noted after swimming training using a device called fixed Push Off Point (POP; Toussaint and Vervoorn, 1990).

Swimming performance in the 400 metres (400_{FULL}) did not improve significantly after the swimming training programme. This finding suggests that the changes associated with improvements in 200_{ARMS}, DPP, and TET_{ARMS} due to arms-only training and 200_{LEGS} and DPK due to legs-only training, do not necessarily translate into improved 400_{FULL} swimming performance. These findings agree with those of previous studies, where swimming performance remained unchanged after an 8-week swimming and resistance training programme (Tanaka et al., 1993) and also after three different types of tapering (Hooper et al., 1998). Tanaka et al. (1993) suggested that the lack of a positive transfer between dry-land strength gains and propulsive force may be due to the specificity of training. Similarly, the swimming training percentage used for arms-only (14%) and legs-only (16%) used in this study, may have not been adequate to bring about improvements in 400-metre swimming performance.

It was shown in this study that it is possible to assess training adaptations in the endurance capacity of the arms and the legs due to arms- or legs-only swimming training using dry-land ergometry. This type of ergometry might be useful in assessing the changes due to swimming training of the arms or the legs in physiological measures, such as oxygen uptake and ventilatory threshold in relation to exercise intensity. Such testing has been shown to be problematic when using water-based methods, such as the swimming flume, where it has been difficult to assess physiological responses to arms-only or legs-only swimming at the same swimming speed (Holmér, 1974). The findings of this study demonstrated that dry-land

ergometry can serve as a valuable tool to monitor and evaluate the effects of arms- or legs-only swimming training on the aerobic capability and movement economy of the arms or the legs. Physiological measures such as oxygen uptake and ventilatory threshold of swimmers can be determined in the laboratory using dry-land ergometry. Such assessments might be of use to sport physiologists, who are interested in investigating the effects of different types of swimming training on the upper and lower body physiology of swimmers. Further research into comparing gas exchange responses between dry-land and free swimming needs to be undertaken to ascertain the validity of dry-land ergometry in swimming.

CHAPTER 5

CARDIOPULMONARY RESPONSES TO ARMS-ONLY, LEGS-ONLY AND COMBINED ARM-LEG DRY-LAND EXERCISE AND FREE SWIMMING

This chapter discusses the agreement between physiological measures derived from dry-land ergometry and water-based testing. The cardiopulmonary responses of oxygen uptake and heart rate to dry-land arm-pulling, leg-kicking and combined arm-leg exercise are compared to respective responses to arms-, legs-only and whole-body free swimming. A review of literature with regard to the study of oxygen uptake responses to upper, lower and whole-body exercise in other sports and in swimming is given in the introduction. Also, the rationale for studying such responses using dry-land ergometry is stated in the same section. A detailed description of the different equipment and exercise protocols used in this study is presented in the methods and the results of the measurements are given in the results section. The differences or similarities in the findings of dry-land and free swimming measurements are presented in the discussion section and will be compared to those of previous research. These findings establish the appropriateness or inappropriateness of dry-land ergometry to assess the exercise capabilities of swimmers by reflecting water-based measurements. Part of this work has been presented (poster) and published (abstract) in: Konstantaki M., Swaine I.L., Winter E.M. Maximal and submaximal cardiopulmonary responses to whole-body simulated swimming. In: Parisi P., Pigozzi F., Prinzi G. (eds), *Proceedings of the 4th Annual Congress of the European College of Sport Science*, p. 382, Rome University Institute of Motor Sciences, Rome, Italy, 1999.

5.1. Introduction

There have been several studies that have assessed arm peak oxygen uptake ($\dot{V}O_{2peak}$) in swimmers using dry-land ergometry. One study employed arm cranking and assessed the anaerobic and aerobic components in sprint and middle-distance swimmers (Mercier et al., 1993), but this method has been shown to have poor specificity with swimming (Strømme et al., 1977). Other studies have used swim bench testing and have assessed the cardiopulmonary responses to exercise (Swaine and Zanker, 1996), the effect of swimming training on arm $\dot{V}O_{2peak}$ of prepubertal girls (Obert et al., 1996) and the acute responses to surgical tubing and swim bench interval exercise (Sexsmith et al., 1992). The relationship between arm $\dot{V}O_{2peak}$ responses to dry-land and water-based testing has been investigated in only one study. This study compared arm $\dot{V}O_{2peak}$ between swim bench exercise and arm stroke in a swimming flume (Ogita and Taniguchi, 1995). There have not been any published comparisons of the leg $\dot{V}O_{2peak}$ responses to dry-land and free swimming.

There are few studies of the $\dot{V}O_{2peak}$ responses to leg exercise in swimmers using water-based testing, but these studies have used free (Adrian et al., 1966) and flume (Ogita et al., 1996) swimming. The absence of studies of the $\dot{V}O_{2peak}$ responses to leg exercise in swimmers has been mainly due to the established notion that the only function of the leg action in front crawl swimming is to keep the body in a streamlined position and thereby, reduce drag (Councilman, 1980). Determinations of the $\dot{V}O_{2peak}$ responses to leg exercise using dry-land ergometry have been hindered due to absence of an appropriate leg-kicking device. Recently, a leg-kicking ergometer has been developed (Swaine, 1997), which has enabled the $\dot{V}O_{2peak}$ responses to leg-kicking to be assessed (Konstantaki and Swaine, 1999). The extent to which measurements of the $\dot{V}O_{2peak}$ responses to leg-kicking exercise using this dry-land ergometer may reflect respective measurements in the water was not investigated in those studies.

The oxygen uptake responses to whole-body swimming ($\dot{V}O_{2peak}$) have been explored in many studies using water-based methods. These studies have included the mechanical efficiency of front crawl swimming (Toussaint et al., 1990), the comparison of maximal oxygen uptake between tethered and free swimming (Rinehardt et al., 1991), the oxygen uptake responses to swimming in a hypobaric hypoxic environment (Ogita and Tabata, 1992) and the relationship between oxygen uptake, stroke rate and swimming velocity in competitive swimming (Wakayoshi et al., 1995). There have not been any investigations of the $\dot{V}O_{2peak}$ responses to dry-land whole-body exercise. This has been mainly due to absence of appropriate ergometry. A combined arm-leg ergometer, that incorporates the use of the arm-pulling and leg-kicking ergometers, has been recently developed (Swaine et al., 1998). This new ergometer might aid assessments of the $\dot{V}O_{2peak}$ responses to whole-body exercise in swimmers using dry-land ergometry.

An investigation into the oxygen uptake and heart rate responses to arms- and legs-only and whole-body exercise might provide insight into the metabolic demands of the upper and lower body compared to whole-body of swimmers. Such findings would be useful to sport physiologists in determining the contributions of the upper and lower body during whole-body exercise. The comparison of arm, leg and whole-body $\dot{V}O_{2peak}$ responses to dry-land and free swimming would demonstrate whether dry-land measurements agree with respective water-based measurements. These findings would validate the use of dry-land ergometry as a alternative method for assessing physiological characteristics of swimmers. The purpose of this study was to ascertain the degree of agreement between dry-land and water-based measurements of peak oxygen uptake and heart rate responses to arms-only, legs-only and whole-body exercise in swimmers.

5.2. Methods

5.2.1. Subjects

Five male swimmers (mean ± SD; body mass: 67 ± 5 kg, stature: 1.74 ± 0.06 m, age: 19 ± 3 years) and four female swimmers (mean ± SD; body mass: 62 ± 3 kg, stature: 1.63 ± 0.04 m, age: 17 ± 4 years) provided informed consent and participated in the study. Subjects were all competitive club swimmers. For the three months prior to the study all swimmers performed on average 4-5 training sessions per week. Their training mileage averaged 16,000 ± 3,000 m per week. To allow familiarisation with the test procedures, all subjects reported to the laboratory or the swimming pool on two separate occasions, respectively. They all performed six incremental exercise tests to exhaustion using either dry-land exercise or free swimming. There were three dry-land tests; an arm-pulling, a leg-kicking and a combined arm-leg test and three free swimming tests; an arms-only, a legs-only and a full stroke front crawl test. The dry-land tests were performed in the laboratory using an interfaced swim bench and a leg-kicking ergometer and also these two ergometers in combination. The swimming tests were performed in a 23-metre (25-yard)) swimming pool.

5.2.2. Equipment

5.2.2.a. The arm-pulling and leg-kicking ergometers

These used an interfaced swim bench (H. and M. Engineering, Gwent, Wales, UK) and a leg-kicking ergometer (University of Warwick, Warwick, UK). The leg-kicking ergometer is an adaptation of the swim bench. The operation and calibration of this ergometer have been described previously in Chapter 2.

5.2.2.b. The combined arm-leg ergometer

This ergometer incorporated the use of the arm-pulling (swim bench) and leg-kicking ergometers. A purpose-built swing frame with a suspended platform (De Montfort University Bedford, Bedford, UK) was specially designed to support the upper body and hips of the swimmer and was held at approximately 1 m from the ground. The

arm-pulling (swim bench) and the leg-kicking ergometers were arranged in front and behind the platform, respectively. The distance at which these two ergometers were placed in relation to the platform depended on the stature of the swimmer and was adjusted accordingly for every subject. The swimmers had to lay prone on this platform and put their hands in the hand paddles attached to the swim bench, whilst they could also put their feet in the stirrups on the leg-kicking ergometer (Plate 14). To achieve a comfortable posture on the platform and allow full range of motion, the swimmers' knees should be slightly bent when feet were placed in the stirrups, whereas arms should be slightly bent at the elbow when placed in the hand paddles. To replicate the front crawl swimming action, the swimmers had to pull backwards on the hand paddles with alternating arms, whilst kicking upwards and downwards with alternating legs.

5.2.3. Heart rate instrumentation

This used a waterproof heart rate monitor with a wrist receiver (Polar Vantage, POLAR Electro, Kempele, Finland) to enable measurements of heart rate during all tests. The receiver was set to record heart rate at 5-second intervals throughout all tests. All male subjects wore an adhesive strap around the chest area to keep the heart rate monitor in place during swimming.

5.2.4. Gas analysis equipment

Gas analysis equipment used a portable device (COSMED K2, Rome, Italy) to allow measurements of oxygen uptake throughout all tests. This comprised a transmitter and a receiver unit operating on re-chargeable batteries. The calibration and operation of this equipment has been described in detail in Chapter 2 of this thesis. The receiver unit was set to record gas exchange readings and compute oxygen uptake every 15 seconds throughout the tests. These readings were displayed on screen, whilst also being printed during testing. The readings were later averaged for every 30 seconds of each test.

5.2.5. The dry-land exercise tests

5.2.5.a. The arm-pulling and leg-kicking tests

The exercise protocol used for the arm-pulling and leg-kicking tests in this study has been described in detail in Chapter 4 of this thesis. Oxygen uptake ($\dot{V}O_2$) and heart rate (HR) were continuously recorded throughout the test at 5-second intervals and at exhaustion ($\dot{V}O_{2peak}$; HR_{peak}).

5.2.5.b. The combined arm-leg test

The subjects lay prone on a specially designed platform, which was suspended from a purpose-built swing frame (Plate 14). A strap was worn around their torso to keep them in place whilst exercising. The swim bench was placed at approximately 1-metre distance in front of the platform and the subjects placed their hands in the hand paddles. The leg-kicking ergometer was placed in line with the swim bench and the distance was adjusted accordingly to allow knee flexion when the swimmers placed their feet in the stirrups. The swimmers wore a heart rate monitor to record heart rate and a mouthpiece was connected to portable gas analysis equipment to record oxygen uptake in the same way as described previously for the arm-pulling and the leg-kicking tests. The exercise intensity was set to increase by 7.5 $W \cdot min^{-1}$ with a starting power output of 20 W. Subjects were instructed to replicate the front crawl swimming action by pulling and kicking in a synchronised action.

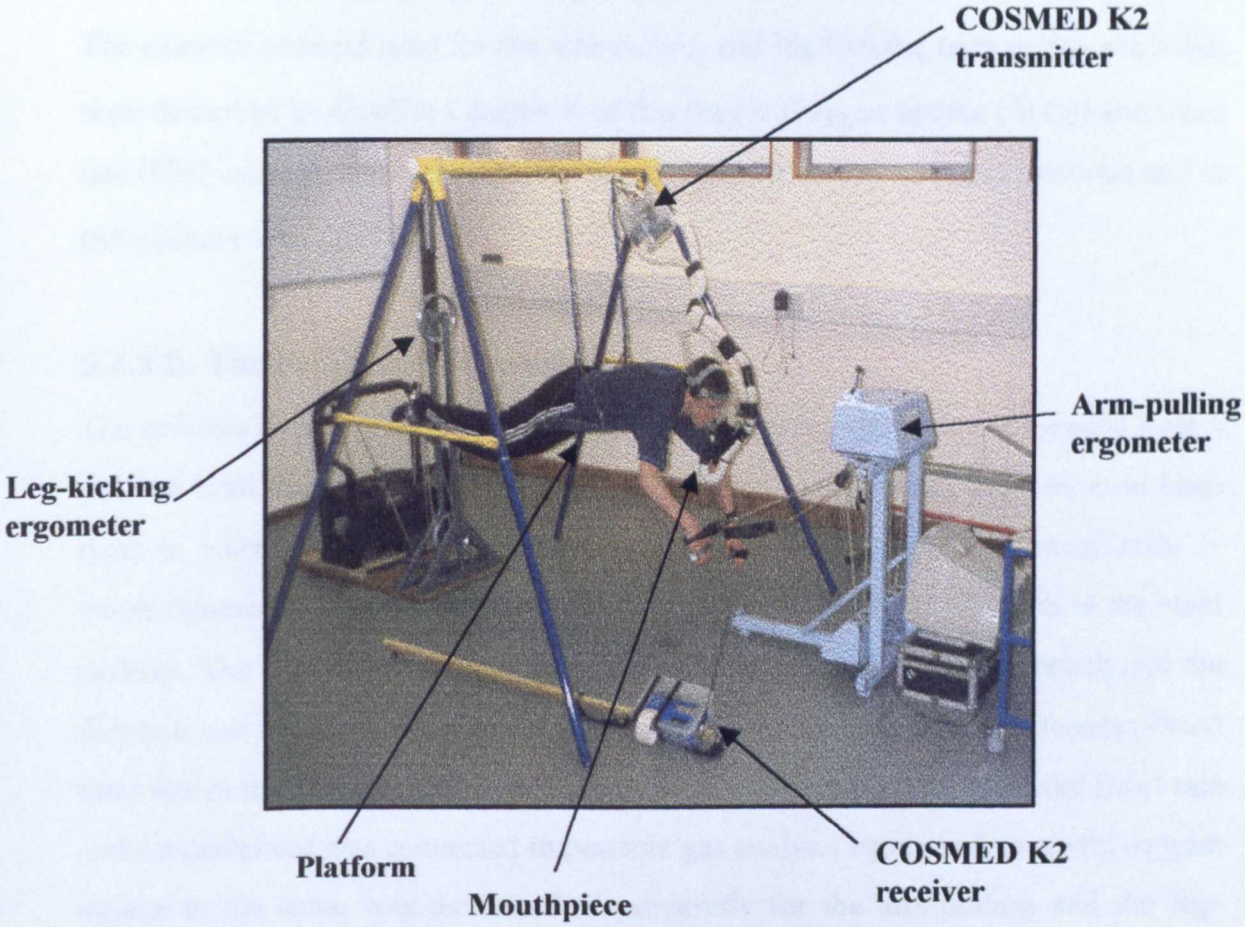


Plate 14. The combined arm-leg test showing the positioning of the arm-pulling and leg-kicking ergometers, the COSMED K2 apparatus, the steel frame and the suspended platform.

5.2.6. The swimming tests

5.2.6.a. The arms-only test

Subjects were asked to perform the front crawl swimming action using their arms-only. A pull-buoy was used to keep the swimmers' legs afloat and minimise drag. To determine the appropriate starting speed and increments for this test, five swimmers volunteered to swim two lengths at their slowest and fastest speed using their arms-only whilst wearing a mouthpiece with headgear attached. Their times were recorded and these data were used in the design of the exercise protocol. An incremental exercise test was specially designed (De Montfort University Bedford, Bedford, UK) to elicit peak heart rate and peak oxygen uptake responses within 15-20 minutes. This test used a series of audio signals (bleeps) recorded on a tape recorder (Tandberg Audio Tutor TAN771). The signals were generated by a two-channel process timer (Electronic Developments, Hampton, Middlesex, UK), which was linked to a tone generator developed by a technician. Subjects had to complete the first length of a 23-metre (25-yard) swimming pool in 28 seconds and length completion time was set to decrease by 0.25 seconds for every length thereafter (i.e. 1 second per 92 metres [100 yards]). Swimmers had to swim to the opposite end of the pool, turn around (without tumble turning) and wait for the audio signal to sound before starting to swim again. This audio signal was played by a tape recorder and was sounded using an 80 W speaker. The first 92 metres were regarded as warm-up and were excluded from the measurements. Swimmers wore a heart rate monitor with wrist receiver and a mouthpiece with headgear attached (Plate 16) to allow measurements of heart rate and oxygen uptake, respectively during the test. Subjects had to breathe through the mouthpiece at all times during the test. This mouthpiece was connected via two respiratory hoses to portable gas analysis equipment, which was placed in a plastic container and was carried along the pool side by the tester following the swimmer (Plate 15). The test was terminated at volitional exhaustion or when the subjects failed to complete two consecutive lengths within the time limit.

5.2.6.b. The legs-only swimming test

Subjects were asked to perform the front crawl leg-kicking action using a kick board to support their upper body and maintain a low resistance posture in the water. A slightly different exercise protocol was designed for the purposes of the legs-only test using the same software. Swimmers had to complete the first length of the 23-metre (25-yard) pool in 32 seconds. The length completion time was set to decrease by 0.25 seconds for every length thereafter. The first two lengths of the legs-only test were regarded as warm-up and were excluded from the measurements. The same procedures pertaining to oxygen uptake and heart rate measurements were followed for the legs-only test as for the arms-only test.

5.2.6.c. The full-stroke swimming test

Subjects were asked to perform the full stroke front crawl swimming action using both their arms and legs. A different exercise protocol was designed for the full stroke test using the computer software named above. The starting speed for this test was determined from preliminary tests were the swimmers were asked to swim two lengths full stroke front crawl, one at their slowest and one at their fastest speed, whilst wearing the mouthpiece with the attached headgear. Their times were recorded and these data were used in the design of the exercise protocol for this test. The swimmers had to complete the first length of a 23-metre (25-yard) swimming pool in 26 seconds and the length completion time decreased by 0.25 seconds for every length thereafter. The first 92 metres (100 yards) were regarded as warm-up and were excluded from the measurements. The rest of the testing procedures were the same as for the arms- and legs-only swimming tests.

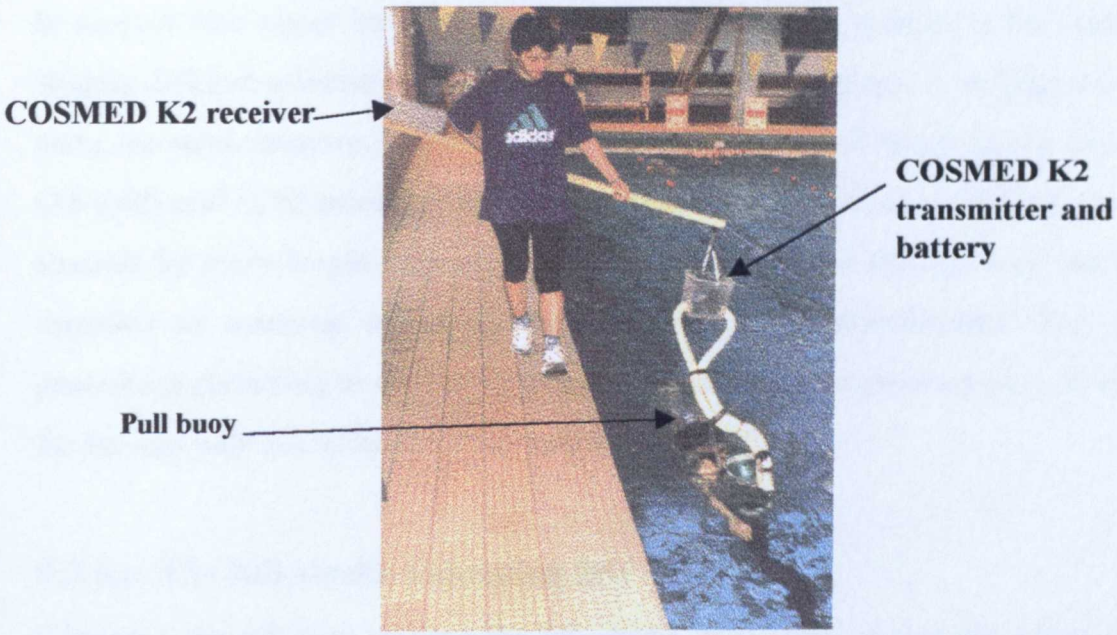


Plate 15. The arms-only swim test showing the mouthpiece and the COSMED K2 apparatus.

Plate 16. The specially designed mouthpiece used for collection of expired air during the swimming tests.

5.3. Statistical analysis

Analysis of variance (ANOVA) with repeated measures on one factor (tests) was employed to identify significant differences in $\dot{V}O_{2peak}$ and HR_{peak} between dry-land exercise and free swimming. The levels of significance were set at $P<0.05$. The relationship between heart rate and oxygen uptake responses to arms, legs-only and whole-body exercise was also explored.

5.4. Results

There were no differences in the HR_{peak} responses between the dry-land tests (arm-pulling: 168 ± 15 beats·min^{-1}; P=0.3, leg-kicking: 171 ± 12 beats·min^{-1}; P=0.5, combined arm-leg: 181 ± 13 beats·min^{-1}; P=0.6). Also, there were no differences in HR_{peak} between the swimming tests (arms-only: 177 ± 14 beats·min^{-1}; P=0.2, legs-only: 173 ± 15 beats·min^{-1}; P=0.4, whole-body: 180 ± 14 beats·min^{-1}; P=0.3). The $\dot{V}O_{2peak}$ responses to whole-body swimming were 10% higher than the $\dot{V}O_{2peak}$ responses to combined arm-leg dry-land exercise (4.12 ± 0.84 l·min^{-1} versus 3.69 ± 0.18 l·min^{-1}; $P<0.05$). and). The $\dot{V}O_{2peak}$ responses to arms-only and legs-only swimming (3.36 ± 0.35 l·min^{-1} and 3.55 ± 0.43 l·min^{-1}, respectively) were not significantly different than the respective responses to dry-land arm-pulling and leg-kicking exercise (3.22 ± 0.43 l·min^{-1} and 3.15 ± 0.54 l·min^{-1}, respectively). These results are shown in Figure 20. The $\dot{V}O_{2peak}$ responses to whole-body exercise in free swimming were higher than the $\dot{V}O_{2peak}$ responses to arms-only and legs-only swimming by 18% and 14%, respectively. Also, the $\dot{V}O_{2peak}$ responses to combined dry-land arm-leg exercise were higher than the $\dot{V}O_{2peak}$ responses to arm-pulling and leg-kicking by 13% and 15%, respectively. The relationship between whole-body $\dot{V}O_2$ and HR was shown to be linear in dry-land and free swimming (r= 0.95 and r=0.94, respectively). An example of the relationship between whole-body $\dot{V}O_2$ and HR in dry-land and free swimming is shown in Figure 21.

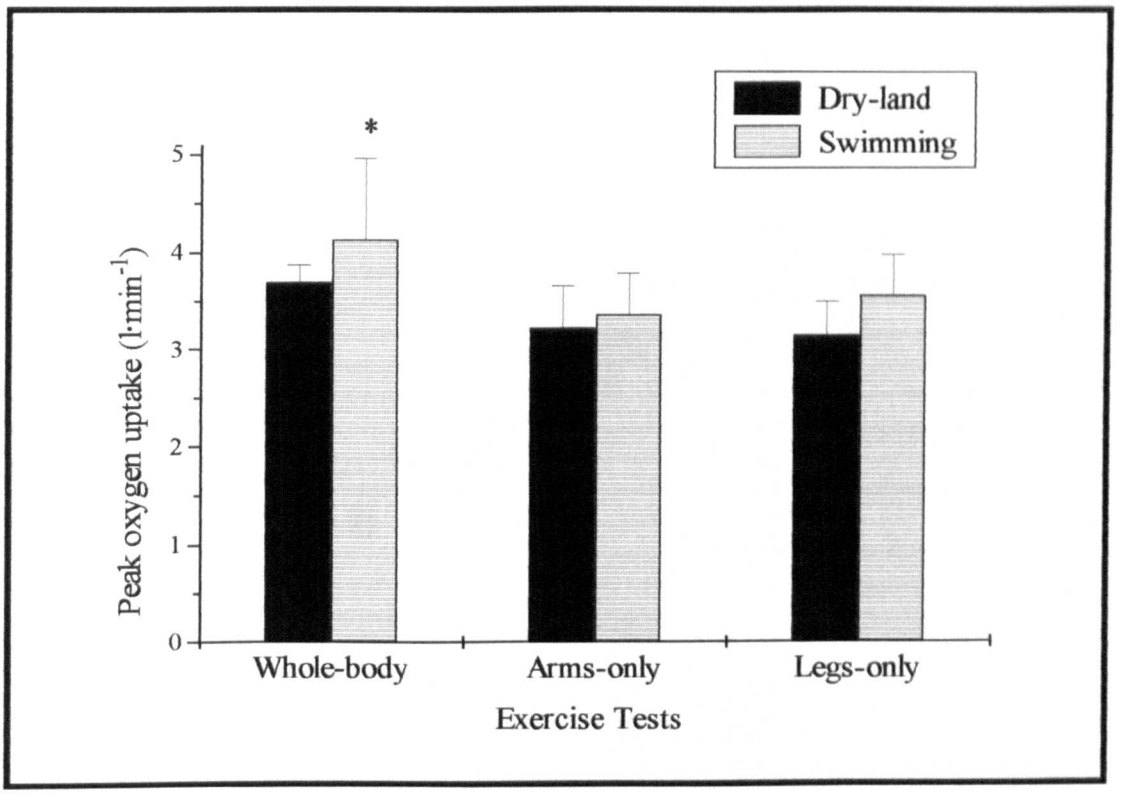


Figure 20. Peak oxygen uptake ($\dot{V}O_{2peak}$; $l \cdot min^{-1}$) responses to arms-, legs-only and whole-body in dry-land exercise and free swimming. Error bars are S.E.M. * Significant at $P<0.05$.

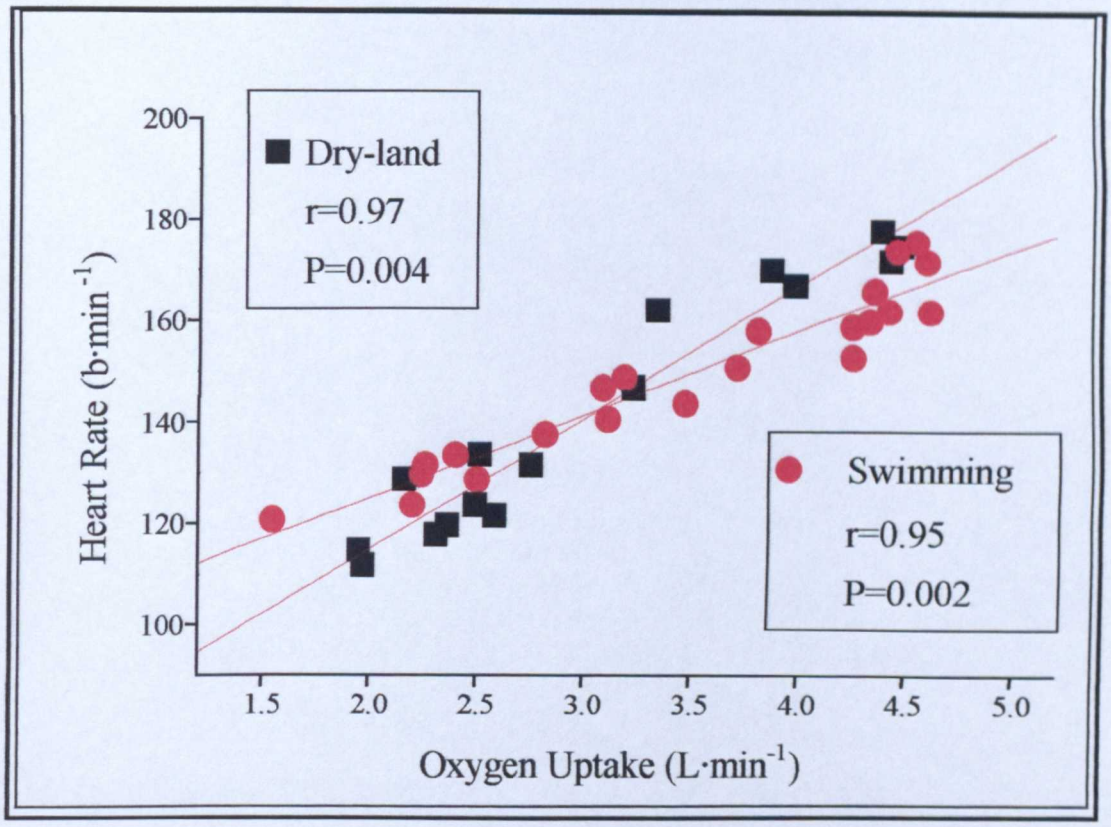


Figure 21. Whole-body oxygen uptake ($\dot{V}O_2$; l·min^{-1}) plotted against heart rate (HR; beats·min^{-1}) in dry-land and free swimming for one subject.

5.5. Discussion

This study demonstrated that the dry-land measurements of peak oxygen uptake and peak heart rate compare well with respective measurements derived from water-based testing. Peak oxygen uptake was greater during whole-body than arms- or legs-only exercise in both exercise modalities; however, whole-body $\dot{V}O_{2peak}$ was also higher in free swimming than in dry-land exercise. Whole-body $\dot{V}O_{2peak}$ in free swimming was 10% higher than in dry-land combined arm-leg exercise. This small difference might be explained by differences in technique that arise from the limited body roll associated with dry-land combined arm-leg exercise. In addition, this difference might also be explained by the documented limitation on chest expansion imposed on the swimmer by the prone posture on the dry-land ergometer (Swaine and Reilly, 1983).

Whole-body $\dot{V}O_{2peak}$ was higher than arms-only or legs-only $\dot{V}O_{2peak}$ in free swimming by 18% and 14%, respectively. Similar differences were observed in dry-land exercise, where combined arm-leg $\dot{V}O_{2peak}$ was higher than arm-pulling or leg-kicking $\dot{V}O_{2peak}$ by 13% and 15%, respectively. These findings are in agreement with those of previous studies where it has been demonstrated that a greater aerobic demand placed upon the body during whole-body exercise compared to arms-only or legs-only exercise. It is well established that when the muscle mass of both arms and legs is required to perform an exercise task, the oxygen demand is higher than it is during arms-only or legs-only exercise (Currie et al., 1992; Hoffman et al., 1996). Similarly, it has been suggested that the addition of arm to leg exercise elicits an increase in $\dot{V}O_{2peak}$ (Reybrouck et al., 1975). Furthermore, these findings agree with previous studies that have assessed peak oxygen uptake using water-based ergometry (swimming flume; Holmér, 1972; Ogita et al., 1996).

Another notable result in this study was that there was no difference between arms- and legs-only $\dot{V}O_{2peak}$ and HR_{peak} in both free swimming and dry-land exercise. This

contradicts previous research findings that have stated that the highest oxygen uptake achieved during exercise with the arms is generally 20-30% lower than leg exercise (Sawka et al., 1983; Sawka, 1986). Similarly, the peak values for heart rate (HR_{peak}) have been found to be significantly lower during arm than leg exercise (Vokac et al., 1975; Magel et al., 1978). These differences have been attributed to the relatively smaller muscle mass of the upper body used in arm ergometry (Miles et al., 1989). Similar differences were not observed in this study. The absence of differences in HR_{peak} responses to upper and lower body exercise might be explained by the fact that the swimmers in this study had a high degree of conditioning in their upper body. Also, the ergometry used in our study was specially designed to engage the muscle groups required by the swimming activity compared to arm cranking and leg cycling used in those studies.

The relationship between $\dot{V}O_2$ and HR was found to be linear in whole-body free swimming and dry-land exercise. These results add to previous findings, where the relationships between oxygen uptake and exercise intensity ($\dot{V}O_2$ versus EI) and heart rate and exercise intensity (HR versus EI) were found to be linear during arm-pulling dry-land exercise in swimmers (Swaine and Zanker, 1996).

It was shown in this study that, with regard to oxygen uptake and heart rate, dry-land measurements compare favourably with respective water-based measurements. These findings could be useful to sport physiologists who wish to investigate the relative contributions of the upper, lower and whole-body aerobic potential of swimmers. Such determinations would also be useful to swimming coaches who are interested in monitoring the improvements due to training or the effects of detraining on power output of the arms, legs and whole-body of swimmers. It has been shown previously that the arm-pulling ergometer (interfaced swim bench) has been useful in assessing the effects of detraining on arm power output of swimmers (Swaine, 1997). Similarly, this type of ergometry could be used to assess the effects of detraining on arm and/or

leg power output and even aid rehabilitation of injured swimmers. More importantly, the continuous assessment of the physiological responses to arm-pulling, leg-kicking and combined arm-leg exercise in relation to exercise intensity is now possible to be conducted in the laboratory using the proposed dry-land ergometry. In addition, the main advantage associated with the use of this type of dry-land ergometry in physiological assessment of swimmers is that physiological measures are not influenced by swimming technique. This problem has been associated with all types of water-based testing. Finally, the findings in this study, validate the use of dry-land ergometry as a reliable alternative method that can be used with confidence in assessment of physiological characteristics of swimmers.

CHAPTER 6

GENERAL DISCUSSION

This chapter is set out in three parts. The first part includes an overview of the main findings in the component studies of this thesis, which are discussed in relation to the aims and objectives stated in the Introduction and Literature Review chapter. In particular, this includes discussion of the usefulness of dry-land ergometry in assessment of power output and cardiopulmonary and metabolic measures of swimmers using cross-referencing between the findings of the three component studies in this thesis. Also, in the same part of the General Discussion Chapter, the usefulness of dry-land ergometry to reflect changes due to training in swimming performance is discussed. The second part includes a detailed description of the limitations associated with the use of the proposed dry-land ergometry. Last, the third part outlines ways by which to develop further this equipment and provides directions for future research.

6.1. Dry-land ergometry in assessment of power output of swimmers

Power output was assessed in two of the studies presented in this thesis using dry-land ergometry. In particular, the peak power output responses to arm-pulling and leg-kicking exercise were assessed in trained and untrained swimmers (Chapter 3) and before and after a swimming training programme (Chapter 4). The findings of these studies indicated that it is possible to assess arm and leg power output in swimmers using dry-land ergometry.

The measurement of arm power output of swimmers has been advocated in swimming research. There have been a few studies that have emphasised that improvements in swimming performance are closely associated with increased arm power output (Charbonier et al., 1975; Costill et al., 1983; Toussaint and Vervoorn, 1990; Sharp et al., 1992). However, the measurement of arm power output using water-based methods, such as tethered swimming (Magel et al., 1974) and the MAD system (Hollander et al., 1986) has been criticised due to the fact that propulsive power differs significantly from the power output of the limbs (Toussaint and Beek, 1992). On the other hand, it has been suggested that the use of a dry-land method such as arm-cranking to assess arm power output of swimmers (Hawley et al., 1992) is, due to the specificity of training, less suited to swimmers than arm-pulling exercise using the swim bench (Swaine et al., 1999). In Chapters 3 and 4 of this thesis arm power output was assessed using the arm-pulling ergometer; a swim bench that has been interfaced with a microcomputer to enable quantification of power output. It was shown that it is possible to elicit peak power output responses to arm-pulling exercise using an incremental exercise protocol. The findings of these studies are in agreement with those of previous studies that have used swim bench exercise (Swaine, 1996; Swaine and Zanker, 1996; Swaine, 1997).

The measurement of leg power output of swimmers has not been favoured in swimming research. Traditional theories have supported the notion that the main function of the leg-kick action in front crawl swimming is to keep the body in a

streamlined position and reduce drag (Alley, 1952; Adrian et al., 1966; Laurence 1969; Holmèr, 1974; Councilman, 1977). These theories have been reinforced by findings which have suggested that the contribution of the leg-kick in swimming speed is very small (Hollander et al., 1986; Keskinen and Komi, 1992), but these studies did not use direct measurements of leg power output. Conversely, measurements of leg power output of swimmers have been hindered by the lack of appropriate ergometry. In Chapters 3 and 4 of this thesis, leg power output was assessed using a newly developed leg-kicking ergometer. It was shown that it is possible to elicit peak power output responses to leg-kicking exercise using an incremental protocol. Other studies that have assessed leg power output of swimmers have used a gymnasium resistance machine (Klika and Thorland, 1994) and another type of isokinetic dynamometry (Miyashita et al., 1992), but, due to the different types of ergometry used, any comparison of leg power output with these studies is difficult.

One of objectives in Chapter 3 of this thesis was to investigate whether the peak power output responses to arm-pulling were different to those of leg-kicking in trained and untrained swimmers. The findings showed that trained swimmers could achieve higher peak power outputs (EI_{peak}) during arm-pulling than during leg-kicking exercise, whereas there were no differences between arm-pulling and leg-kicking power output in untrained swimmers. These findings suggested that the distinguishing factor between swimmers of different training status is the degree of conditioning in their arms, even though it was not clear whether these differences were due to increased muscle mass or increased muscle oxidative capacity (Holloszy and Coyle, 1984). It has been postulated that regular overload of the upper body muscle groups brings about changes in the metabolism of the overloaded musculature (Rasmussen et al., 1975; Sawka, 1986; Rinehardt et al., 1992). Also, the values noted for arm-pulling EI_{peak} for the collegiate swimmers in this study compare well with those reported previously for arm-cranking exercise (Enders et al., 1994) and for dry-land ergometry (Swaine, 1997). These findings demonstrated that dry-land ergometry measurements can reflect the enhanced localised metabolism of the arms of trained

swimmers. However, the same differences were not noted for leg-kicking peak power output between trained and untrained swimmers. This finding could be probably attributed to the use of subjects that were untrained swimmers, but highly trained athletes in sports that predominantly engaged the lower body muscle groups and thus, could produce high power outputs during leg-kicking exercise. Alternatively, limitations inherent in the use of the leg-kicking ergometer might have prevented the trained swimmers to perform to their maximum power output capacity during leg-kicking exercise. These are discussed in a later section of this Chapter.

In Chapter 4 of this thesis the peak power output responses to arm-pulling and leg-kicking were not reported, but can be inferred from the measurements of total exercise time (TET). It was shown that before and after training TET during arm-pulling exercise was higher than TET during leg-kicking exercise, meaning that swimmers could sustain higher power outputs during arm-pulling than during leg-kicking exercise. These findings confirm those of Swaine (1997) and also those of Chapter 3 in this thesis, but contradict those of previous studies that have used other types of ergometry (arm-cranking and cycling) to assess the peak power output of the arms and the legs (Reybrouck et al., 1975; Nagle et al., 1984). However, these studies used untrained subjects and did not use swimmers. It appears that the type of dry-land ergometry used in the studies of this thesis reflects the differences in the power output capabilities in the arms and the legs of swimmers.

The assessment of the peak power output responses to arm-pulling and leg-kicking exercise using dry-land ergometry has enhanced our understanding of swimming physiology. The findings in Chapters 3 and 4 of this thesis showed that it is possible to assess peak power output of the arms and the legs of swimmers using the arm-pulling and leg-kicking ergometers. It was also shown that the peak power output responses to arm-pulling exercise are higher than those to leg-kicking exercise. Such an approach has not been possible previously using other types of water-based ergometry or land-based ergometry that has been developed for use by swimmers.

Arm and leg power output measurements using this type of dry-land ergometry could be useful to swimming coaches who are interested in monitoring the changes due to swimming training in the arm and leg power output of their swimmers. Such measurements might also aid the determination of cardiopulmonary and metabolic to arm-puling and leg-kicking exercise of swimmers in relation to exercise intensity.

6.2. Dry-land ergometry in assessment of cardiopulmonary measures of swimmers

The cardiopulmonary measures that were assessed in the three component studies of this thesis were oxygen uptake and heart rate and are discussed in the following sections. The peak oxygen uptake ($\dot{V}O_{2peak}$) responses to arm-pulling and leg-kicking exercise were assessed in trained and untrained swimmers (Chapter 3), before and after a swimming training programme (Chapter 4) and in comparison to arms-only and legs-only swimming (Chapter 5). Also, in Chapter 5 the $\dot{V}O_{2peak}$ and the peak heart rate (HR_{peak}) responses to combined arm-leg exercise where assessed using a newly developed combined arm-leg ergometer. The findings of these studies showed that it is possible to assess the $\dot{V}O_{2peak}$ responses to arm-pulling, leg-kicking and combined arm-leg exercise using dry-land ergometry.

One of the objectives in Chapter 3 of this thesis was to determine whether it is possible to use an incremental exercise protocol to elicit $\dot{V}O_{2peak}$ responses to arm-pulling and leg-kicking exercise when using the arm-pulling and leg-kicking dry-land ergometers, respectively. It was shown that the $\dot{V}O_{2peak}$ responses to arm-pulling noted for the trained swimmers were similar to those reported previously for water-based assessments that have used flume (Holmèr, 1974), tethered (Bonen et al., 1980) and free swimming (Obert et al., 1992) and also for assessments that have used dry-land ergometry (Swaine and Zanker, 1996; Swaine, 1997). The $\dot{V}O_{2peak}$ responses to leg-kicking exercise in the trained swimmers were comparable with those reported previously by Swaine (1997). Furthermore, the $\dot{V}O_{2peak}$ responses to arm-pulling and

leg-kicking exercise in recreational swimmers in Chapter 3 of this thesis compare well with those of previous studies that have used arm-cranking (Washburn and Seals, 1984) and cycling exercise (Åstrand and Saltin, 1961; Reybrouck et al., 1975), respectively.

One of the objectives in Chapter 4 of this thesis was to determine whether dry-land ergometry can detect adaptations due to swimming training in arm and leg $\dot{V}O_{2peak}$ of swimmers. The $\dot{V}O_{2peak}$ responses to arm-pulling and leg-kicking exercise were assessed before and after a six week swimming training programme for the arms-only (ARMS) or the legs-only (LEGS) in two groups of swimmers. The findings showed that $\dot{V}O_{2peak}$ remained unchanged after training in both ARMS and LEGS. There have been studies that have demonstrated significant increases in $\dot{V}O_{2peak}$ following arm-cranking (Davies et al., 1987), cycling (Hardman et al., 1986) and swimming training (Rinehardt et al., 1982), but these studies have used untrained subjects and novice swimmers. The absence of increases in localised $\dot{V}O_{2peak}$ of the arms or the legs of the competitive swimmers in this study might have been due to the amount of additional arms- (+14%) and legs-only training (+16%), which might not have been adequate to induce training adaptations (Pollock et al., 1975).

Another objective in Chapter 4 of this thesis was to ascertain whether dry-land ergometry can detect adaptations due to training in motion economy of the arms and the legs after arms-only or legs-only swimming training. Motion economy was assessed at 60 W ($\dot{V}O_2$-60) during arm-pulling and leg-kicking in both the ARMS and the LEGS groups. It was shown that $\dot{V}O_2$-60 decreased post-training only in the trained segments. These results agree with previous findings in runners and cyclists (Lieber et al., 1989; Foster et al., 1995). Improvements in swimming economy have also been demonstrated after aerobic swimming training (D'Acquisto et al., 1992; Wakayoshi et al., 1993). It appears that dry-land ergometry measurements can reflect the changes due to training in motion economy of swimmers.

One of the objectives in Chapter 5 of this thesis was to investigate whether the $\dot{V}O_{2peak}$ and HR_{peak} responses to combined arm-leg, arm-pulling and leg-kicking dry-land exercise compare with whole-body, arms- and legs-only swimming. The $\dot{V}O_{2peak}$ responses to combined arm-leg exercise were assessed using a newly developed combined arm-leg ergometer that incorporated the use of the arm-pulling and the leg-kicking ergometers. It was shown that combined arm-leg $\dot{V}O_{2peak}$ in dry-land exercise was 10% lower than whole-body $\dot{V}O_{2peak}$ in free swimming. This small difference might be explained by the design limitations associated with the use of the combined arm-leg ergometer, namely the limited body roll, the lack of buoyancy and the posture adopted on the ergometer. These limitations are discussed in detail in a later section of this Chapter. It was also shown in this study that there was no difference between dry-land exercise and free swimming in arms- or legs-only $\dot{V}O_{2peak}$. These results contradict those of previous studies that have suggested that $\dot{V}O_{2peak}$ achieved during exercise with the arms is generally 20-30% lower than leg exercise (Sawka et al., 1983; Sawka, 1986), but these studies have used arm-cranking and cycling ergometry which have been shown to have poor specificity in swimming (Gergley et al., 1984). Another study suggested that $\dot{V}O_{2peak}$ during dry-land arm-pulling exercise is significantly lower (21%) than the $\dot{V}O_{2peak}$ achieved during flume swimming (Ogita and Taniguchi, 1995), but this study compared the responses to discontinuous protocols for dry-land arm-pulling and flume swimming. In addition, it was shown in this study that there was no difference in the HR_{peak} responses between the two exercise modalities in arms-only, legs-only and whole-body exercise. Vokac et al. (1975) and Magel et al. (1978) have documented that the peak values for heart rate are generally lower during arm than leg exercise, but these studies were not conducted on swimmers. Palve and Keskinen (1997) reported that HR_{peak} is significantly higher (10-12 beats·min^{-1}) in legs-only than in arms-only swimming, but this study used a series of set-distance swims and not an incremental exercise protocol as used in this study.

Another objective in Chapter 5 of this thesis was to determine whether the $\dot{V}O_{2peak}$ and HR_{peak} responses to incremental combined arm-leg exercise are different to respective responses to arm-pulling or leg-kicking exercise when using dry-land ergometry. It was shown that combined arm-leg $\dot{V}O_{2peak}$ was found to be higher than arm-pulling or leg-kicking $\dot{V}O_{2peak}$. These findings are in good agreement with previous research and the established notion that a greater oxygen demand is placed upon the body, when the whole-body muscle mass is required to perform the exercise task than only the upper or lower body muscle groups (Miles et al., 1989; Currie et al., 1992; Hoffman et al., 1996). In addition, it has been postulated that the addition of arm to leg exercise elicits an increase in $\dot{V}O_{2peak}$. (Reybrouck et al., 1975). Furthermore, it has been suggested that the optimal contributions of arms and legs to induce $\dot{V}O_{2peak}$ are 20% arm exercise combined with 80% leg cycling (Nagle et al., 1984). The findings of this study are in good agreement with dry-land ergometry in this study confirmed the findings of these studies.

In all three studies of this thesis it was shown that it is possible to assess the $\dot{V}O_{2peak}$ responses to arm-pulling and leg-kicking exercise using the arm-pulling and leg-kicking ergometers, respectively. The $\dot{V}O_{2peak}$ responses to arm-pulling exercise were consistent in all three studies and compared well with other studies that have assessed $\dot{V}O_{2peak}$ using other types of water-based ergometry. The $\dot{V}O_{2peak}$ responses to leg-kicking were comparable to those reported previously by Swaine (1997). The $\dot{V}O_{2peak}$ responses to combined arm-leg exercise were 10% lower than the respective responses to whole-body swimming, whereas the HR_{peak} responses did not differ between the two exercise modalities. The assessment of arm and leg $\dot{V}O_{2peak}$ at the same exercise intensities would aid determinations of the relative contributions of the arms and the legs to whole-body $\dot{V}O_{2peak}$ during combined arm-leg exercise. Such assessments have not been possible using water-based methods such as the swimming flume due to the fact that arms and legs cannot be assessed at the same swimming speeds. Also, the continuous measurement of oxygen uptake during

swimming has been problematic. In all three studies of this thesis it was shown that it is possible to assess the oxygen uptake responses to arm, leg and combined arm-leg exercise using the proposed dry-land ergometry. In addition, arm-pulling exercise has been shown to be more suited to swimmers than arm-cranking exercise (Swaine and Winter, 1999). Also, the possibility that dry-land ergometry offers to assess cardiopulmonary measures in relation to exercise intensity constitutes a more comprehensive alternative to those water-based methods that have assessed physiological measures in relation to swimming speed (Klauck and Ungerechts, 1997).

6.3. Dry-land ergometry in assessment of metabolic measures of swimmers

The metabolic measure that was investigated in one of the studies of this thesis was blood lactate. The peak blood lactate (HLa_{peak}) responses to arm-pulling and leg-kicking exercise and the exercise intensity at a blood lactate concentration of 4 $mmol \cdot l^{-1}$ (EI_{4mM}) were assessed in trained and untrained swimmers (Chapter 3). One of the objectives in this study was to determine whether it is possible to use an incremental exercise protocol to elicit peak lactate (HLa_{peak}) responses to arm-pulling and leg-kicking exercise when using the arm-pulling and leg-kicking dry-land ergometers, respectively. It was shown that HLa_{peak} was higher during arm-pulling than during leg-kicking exercise in both trained and untrained swimmers. Previous investigations that have used arm-cranking and cycling exercise have reported a higher lactacidaemia during arm exercise for any given work rate compared to leg exercise (Bevegard et al., 1966; Stenberg et al., 1967; Klausen et al., 1974; Hagan et al., 1983). The results of this study suggest that arm-pulling exercise induces a higher metabolic strain than leg-kicking exercise and this could be investigated through use of the arm-pulling and leg-kicking ergometers. The EI_{4mM} responses to arm-pulling were found to be higher than the respective responses to leg-kicking in trained swimmers, whereas EI_{4mM} did not differ between arm-pulling and leg-kicking in

untrained swimmers. These results suggested that trained swimmers could achieve higher exercise intensities during arm-pulling before reaching the point of metabolic acidosis compared to leg-kicking. It has been well documented that metabolic acidosis occurs at a higher percentage of the trained athlete's capacity for aerobic metabolism (Coyle, 1983; Gladden, 1989) and that this response is due to training adaptations that favour the production of less lactic acid (Weltman, 1989). It appears that dry-land ergometry could detect the adaptations in the localised metabolism of the arms of the trained swimmers, as this response was not noted for the untrained swimmers in this study.

6.4. Dry-land ergometry in assessment of changes due to training in swimming performance

One of the objectives in Chapter 4 of this thesis was to determine whether the changes due to training in swimming performance of the arms or the legs are reflected in dry-land measurements of endurance. In this study the changes due to training in swimming performance were assessed using a 200 m arms-only, a 200 m legs-only and a 400 m front crawl time trials before and after a six-week swimming training programme for the arms-only (ARMS) or legs-only (LEGS). It was shown that the differences in percent improvement for arms-only or legs-only 200 m swim times (-13% and -2%, respectively) and stroke effectiveness (DPP: +10 ± 3% and DPK: +5 ± 2%) were reflected in the dry-land measurements of total exercise time (TET). Total exercise time improved in the arm-trained group (+25 ± 5%), whereas TET in the leg-trained group remained unchanged after training. A possible explanation for the unchanged leg TET post-training, might be that the % improvement observed for 200 m legs-only swim time and DPK was small and it might have been due to changes in technique (Toussaint and Beek, 1992) rather than due to improvements in the capacity of the muscles to generate ATP aerobically (Gollnick et al., 1972; Turner et al., 1997). These findings raise scepticism about the trainability of the legs and their responsiveness to a specified training stimulus.

However, it appears that dry-land ergometry measurements could reflect the adaptations in localised endurance of the arms which took place due to arm swimming training.

The findings of this study clearly demonstrate that the changes due to swimming training in localised swimming performance of the arms and the legs are reflected in dry-land measurements of arm and leg endurance. Swimming coaches might benefit from the use of this ergometry with regard to monitoring the changes in upper and lower body endurance of their swimmers and relating these changes to improvements in swimming performance (Costill et al., 1985). Also, this type of dry-land ergometry might be useful to sport physiologists, who wish to compare the changes due to arms-only or legs-only swimming training in the separate physiological and metabolic measures of the arms or the legs of swimmers when leg exercise is performed at the same intensities as arm exercise.

6.5. Limitations of dry-land ergometry

There are several limitations in the use of dry-land ergometry in physiological assessment of swimmers that are mainly concerned with the design of this equipment. The main limitation is that these ergometers are used in the confines of a laboratory. Thus, the swimmers have to be taken out of their normal training environment. Ideally, the most realistic approach would be to conduct physiological assessments in the swimming pool. However, there are some physiological assessments that are difficult to carry out in the water. For example, the quantification of upper and lower body power output and the measurement of oxygen uptake and blood lactate during free swimming have been problematic. At this point, it should be clarified that this dry-land ergometry was developed to offer an alternative method to assess those physiological measures that are difficult to be performed in the water and not in any case to replace water-based testing.

Another limitation is that the main factors that facilitate or restrict forward motion in the water (buoyancy and drag, respectively) are not present in dry-land ergometry. The swimmer is asked to replicate the swimming action on the dry-land ergometers, but this unavoidably causes alterations in technique. Such alterations in technique of the swimmer are associated with the use of all three dry-land ergometers presented in the component studies of this thesis.

The most important limitation of the arm-pulling ergometer (swim bench) is the posture the swimmer has to adopt on the ergometer during exercise. Lying prone on a hard surface, such as the swim bench compresses the chest cavity and therefore, limits chest expansion. This according to Swaine and Reilly (1983) can influence ventilation during maximal exercise, thereby limiting oxygen consumption and hindering maximal exercise performance. Such an effect, seemingly, is not present during exercise in the water since buoyancy supports the swimmer's body. This probably does not have such an impact on ventilation. Also, this particular prone posture on a stationary surface does not allow the body to roll during exercise, as is the case during swimming itself. In Chapter 3 of this thesis it was shown that untrained swimmers achieved higher blood lactate values during arm-pulling exercise than trained swimmers. It was suggested that the trained swimmers probably stopped exercising due to breathing restrictions caused by the adopted posture on the arm-pulling ergometer and not due to metabolic acidosis.

The design of the arm-pulling ergometer does not allow for over arm recovery, which is what the swimmer uses during swimming itself. Instead, a different type or recovery called under-arm recovery is used. This, of course, causes alterations in arm movement during the recovery phase of the swimming action. For example, in over-arm recovery there is considerable angle of elbow flexion, which enables the swimmer to recover faster and at a lower energy expenditure (Hay, 1986). A similar angle of elbow flexion is not observed for under-arm recovery in dry-land ergometry. However, it was shown in the component studies of this thesis that physiological

measurements do not seem to be greatly affected by such alterations in technique. It was shown in Chapters 3, 4 and 5 of this thesis that the peak oxygen uptake responses to arm-pulling exercise compare well with respective responses to flume (Holmèr, 1974), tethered (Bonen et al., 1980) and free swimming (Obert et al., 1992).

The design of the leg-kicking ergometer presents limitations that are associated with the limited range of movement during leg-kicking exercise. The stirrups are placed in a fixed position and this limits knee and ankle flexion. This differs from performing leg-kicking in the water, where maximum knee and ankle flexion is not restrained. Also, to use the leg-kicking ergometer, the swimmer must adopt a prone posture and rest their pelvis on the swim bench. It is well known that leg-kicking action in the water originates in the hips (Hay, 1986). During leg-kicking in the water the body of the swimmer is supported by buoyancy and this enables hip movement. The limited hip, knee and ankle flexion may hinder leg-kicking performance on dry-land against high intensities of exercise. These limitations might explain the absence of differences in the peak power output responses to leg-kicking between trained and untrained swimmers (Chapter 3) and also the 10% higher peak oxygen uptake responses to whole-body swimming compared to combined arm-leg dry-land exercise (Chapter 5). However, the extent to which the limitations in the design of the leg-kicking ergometer has affected the measurements in these studies is not known and needs to be investigated using cinematography.

Limitations associated with the use of the combined arm-leg ergometer are mainly concerned with the design of this equipment and the absence of an appropriate resistance device to measure power output of leg-kicking during combined arm-leg exercise. First, the swimmer has to adopt a prone posture on a platform suspended from a purpose-built steel frame. This arrangement allows for limited body roll and hip movement during combined arm-leg exercise when compared to whole-body free swimming. Second, when using the combined arm-leg ergometer, power output of the arms can be computed using the interface unit of the swim bench. However, the

power output of leg-kicking during this type of exercise cannot be computed due to absence of a second interface unit. For this reason, in Chapter 5 of this thesis it was not possible to assess the peak power output responses to leg-kicking during combined arm-leg exercise and thus, the cardiopulmonary responses to leg-kicking could not be related to exercise intensity.

6.6. Future developments in the use of dry-land ergometry

Based on the findings presented in this thesis, it appears that the proposed dry-land ergometry could be a useful tool in physiological assessment of swimmers. It was shown that this type of ergometry was useful in differentiating between physiological responses in trained and untrained swimmers (Chapter 3) and in detecting changes due to swimming training in the separate physiological responses of the arms and the legs of swimmers (Chapter 4). In addition, it was shown that dry-land ergometry measurements compare well with respective water-based measurements (Chapter 5). It becomes apparent that dry-land ergometry is, indeed, a useful alternative method to water-based testing for those physiological assessments which are difficult to conduct in the water. Conversely, the use of dry-land ergometry in physiological assessment of swimmers presents several limitations that are mainly associated with the design of this equipment. There is space for improvement in the current design of dry-land ergometry. Therefore, it is important to address the limitations in the design of dry-land ergometry before further physiological assessments are carried out.

In a historical note, dry-land ergometry has passed through a few stages of development. In the late 1970s, the increase in popularity for strength training of swimmers created the need for a dry-land exerciser that could incorporate resistance exercise and would allow the swimmer to replicate as closely as possible the swimming action (Meisel, 1980). This need led to the development of the 'biokinetic' swim bench. Initially, the swim bench was solely used as a strength training device, but, due to the opportunity it offered to measure power output, it was later used in research to assess physiological measures of swimmers (Meerloo et al., 1988; Reilly

and Marshall, 1991; Ogita and Taniguchi, 1995; Swaine and Zanker, 1996). However, the swim bench measurements were criticised due to absence of leg-kicking. At this stage, the need for a new ergometer that could be used to assess the responses to leg-kicking exercise was identified. This need led to the development of the leg-kicking ergometer (Swaine, 1997) and assessment of leg-kicking power output was then possible (Konstantaki and Swaine, 1999; Konstantaki et al., 1999). Soon after this stage, the focus of research was to investigate the physiological responses to combined arm-leg exercise in an attempt to identify differences or similarities in the separate physiological responses of arms and legs when these two segments are exercised simultaneously. The most recent development in dry-land ergometry was the construction of a combined arm-leg ergometer (Swaine et al., 1998). This new ergometer incorporates the use of the arm-pulling and the leg-kicking ergometers and has enabled assessment and manipulation of power output from arm-pulling, leg-kicking during combined arm-leg exercise. The phases of development of dry-land ergometry are summarised in Diagram 10.

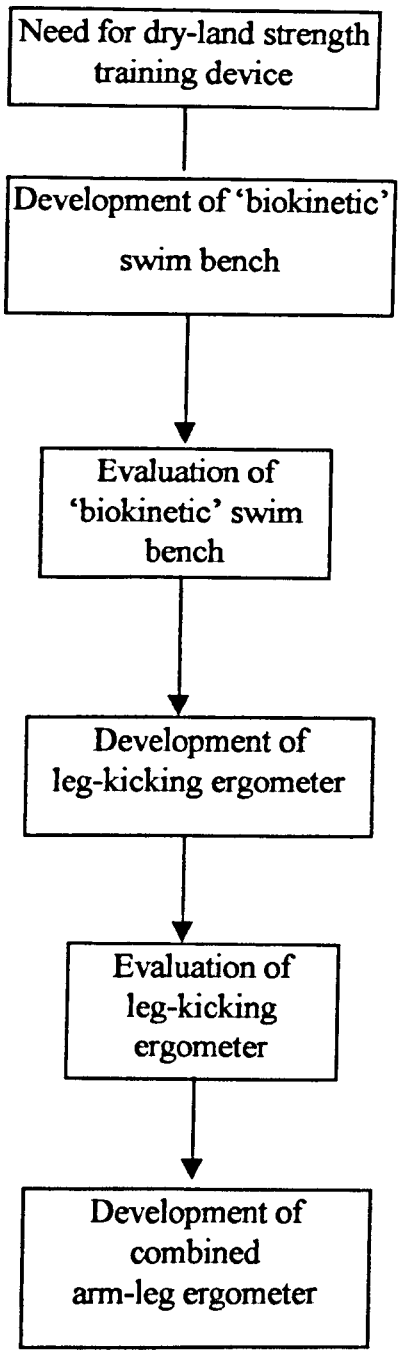


Diagram 10. Stages of development of dry-land ergometry.

The advances in the development of dry-land ergometry have followed a similar trend with other forms of ergometry. For example, the need to find an objective method to identify the variations in cardiorespiratory fitness led to the development of the bicycle ergometer (von Döbeln, 1954). The world's first bicycle ergometer was developed by Bouny, a French medical student, in 1896 (Hollmann and Prinz, 1997). The use of the bicycle ergometer became increasingly popular, due to the fact that bicycling was a simple form of work that could engage large muscle groups and was suitable to test the physical conditioning of both trained and untrained individuals (Åstrand, 1956). Later, the bicycle ergometer was modified to its current state (with one wheel) and is since called the cycle ergometer (Åstrand and Rodahl, 1970). However, due to the 'specificity of training' principle (Strømme et al., 1977), the cycle ergometer was deemed inappropriate to be used in physiological testing of racing cyclists. Immediately, the need to closely replicate the observed conditions relating to the rolling resistance and wind resistance encountered when riding a bicycle on the road led to the development of a laboratory-based wind load simulator (Firth, 1981). More recently, an electromagnetically controlled ergometer was developed to 'ergonomically fit the rider' and ascertain that the mechanical efficiency and the physiological responses are not altered by ergonomic design as is the case with friction-braked ergometers (Seifert, 1991).

Even though the developments in dry-land ergometry have satisfied temporarily the some needs of research, there are limitations in the design of these equipment that ought to be overcome before further research is carried out. These limitations have been discussed in detail in the previous section. First and foremost, there are the problems of limited body roll and restricted breathing caused by chest compression due to the prone posture of the swimmer on a fixed surface (bench) when using the arm-pulling ergometer (Swaine and Reilly, 1983). The problem of chest compression was partly circumvented with the construction of a suspended platform specially designed not to obstruct the thorax (Swaine et al., 1998). With this arrangement, the mass of the swimmer is, indeed, better supported compared to the previous

arrangement. However, the pressure of supporting the swimmer's body is now transferred solely to the abdominal cavity, which may no longer restrict breathing, but may cause discomfort to the exercising individual. In addition, the suspended platform does not address the problem of limited body roll. It is possible that a platform that would incorporate an air mattress might provide a more comfortable surface for the swimmer to lie on and also a more realistic approach to the buoyancy conditions experienced in free swimming. Also, it might be possible to allow or increase body roll, if a system of springs that would stretch and recoil according to the movement of the swimmer is incorporated in the suspension mechanism.

The main limitation in the design of the leg-kicking ergometer is associated with the relatively low speed at which the pulleys can exert force, which does not allow for replication of the 6-beat leg-kicking action used in front crawl swimming (Hay, 1986). Also, the fixed position of the inverted metal stirrups on the vertical stantion of the ergometer does not allow for adequate hip, knee and ankle flexion during leg-kicking exercise as is the case in free swimming (Hay, 1986). It is not clear whether these limitations in the design of the leg-kicking ergometer affect leg-kicking performance at high exercise intensities, but they almost certainly cause alterations in the leg-kicking technique. A suggestion would be to design a leg-kicking ergometer that will provide for increases in speed instead of increases in the leg-kicking rate; perhaps, a device similar to the pulley-rope system of the arm-pulling ergometer. Also, it might be an idea to replace the metal stirrups with leather straps and attach these to the non-stretch rope to increase flexibility of the hip, knee and ankle joints during the different phases of the leg-kicking action.

The development of the combined arm-leg ergometer (Swaine et al., 1998) has partly solved the problem of assessing physiological responses to arm and leg exercise when these two segments are exercised simultaneously. During such assessments resistance to arm-pulling is offered by a rotating clutch device according to the velocity at which the pulley-ropes are extended (range: 1.9 - 3.0 $m \cdot s^{-1}$; Swaine and Zanker, 1996). A

transducer unit is positioned at the apex of a 'v' shaped arrangement of the pulley-ropes and samples force and distance during each pull at 100 Hz (Swaine et al., 1998). This way power output during arm-pulling can be calculated by interfacing with a microcomputer. It was shown in Chapter 3 of this thesis that the computation of power output during leg-kicking was possible through use of the resistance and transducer unit of the arm-pulling ergometer. Nevertheless, the computation of arm-pulling and leg-kicking power output during combined arm-leg exercise is not currently possible since there is only one resistance and transducer unit. Therefore, a second resistance and transducer unit, identical to that of the arm-pulling ergometer, needs to be developed. It would then be possible to investigate the contribution of arms and legs to whole-body physiological responses in relation to arm-pulling and leg-kicking power output, when these two segments are exercised simultaneously. The advanced design of the combined arm-leg ergometer is shown in Diagram 11.

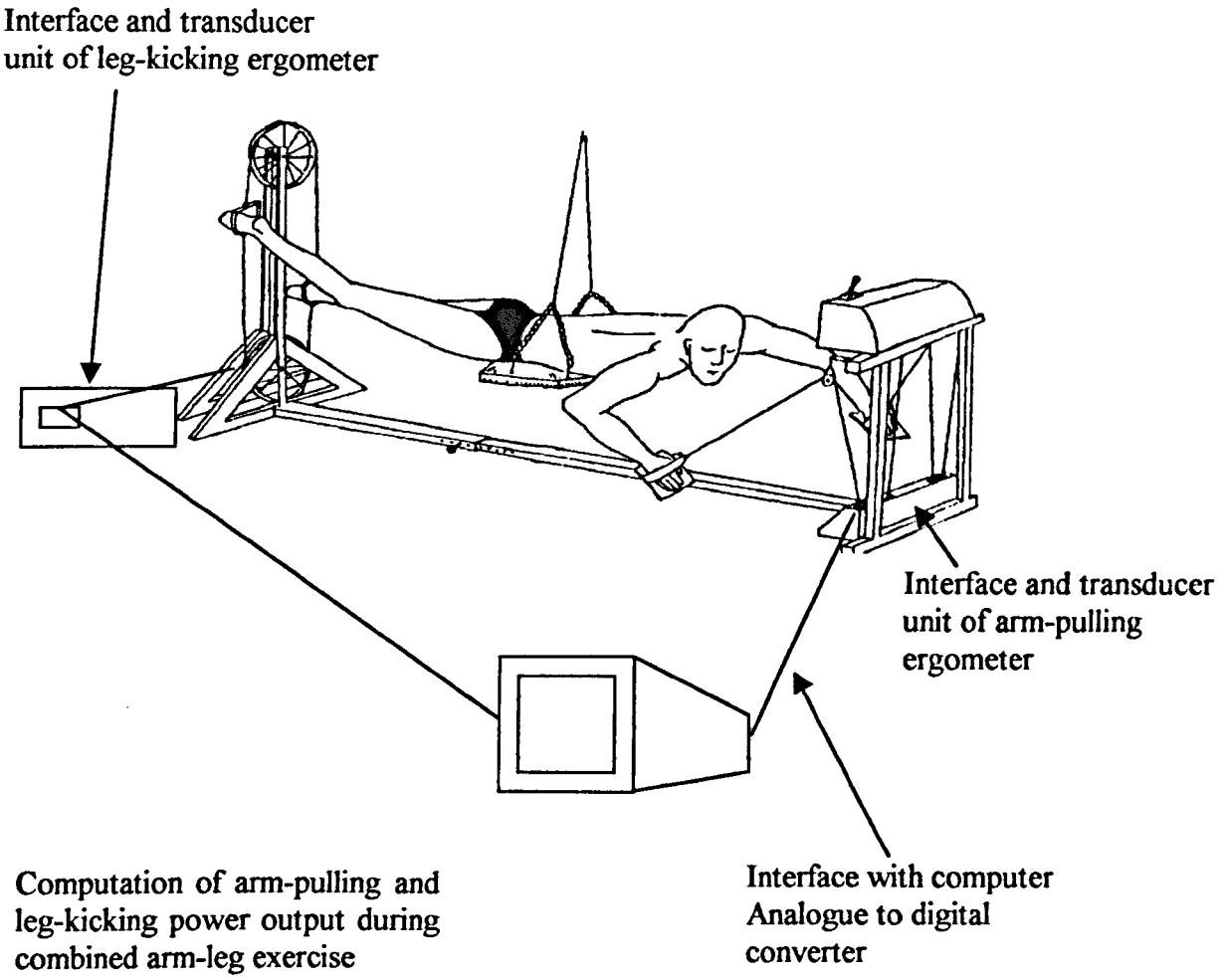


Diagram 11. The proposed future structure of the combined arm-leg ergometer (Permission to reproduce the main diagram has been sought from Swaine et al.: A dry-land ergometer for the assessment and manipulation of power output from arm-pulling, leg-kicking and whole-body simulated swimming. In: Haake S.J. (ed.) *The Engineering of Sport, Design and Development,* Blackwell Science, University Press, Cambridge, pp. 93-98, 1998.

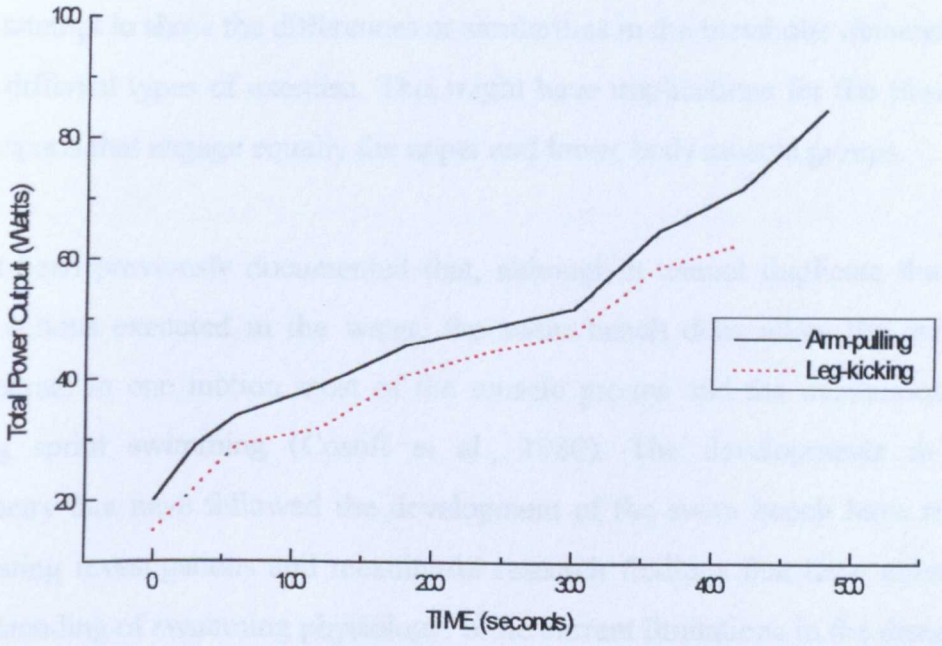


Figure 22. An example of the computation of the arm-pulling and leg-kicking power output during combined arm-leg exercise.

A closer replication of the front crawl arm-pulling, leg-kicking and whole-body action on the respective dry-land ergometers would allow more realistic measurements of the physiological responses to these three different types of exercise. Such assessments might enhance our understanding of the differences in the physiological responses to arm-pulling and leg-kicking when these two segments are exercised simultaneously and might have implications for the design of more effective swimming training programmes. In parallel, the amount of exercising musculature during incremental arm-pulling, leg-kicking and combined arm-leg exercise could

also be investigated using electromyography. Such assessments would aid determinations of muscle fibre recruitment during exercise in swimmers and would be useful in quantifying the amount of exercising musculature at given power outputs. Furthermore, the blood chemistry profile of swimmers during continuous incremental arms-, legs-only and whole-body exercise could be explored at given power outputs in an attempt to show the differences or similarities in the metabolic demands of these three different types of exercise. This might have implications for the physiology of other sports that engage equally the upper and lower body muscle groups.

It has been previously documented that, although it cannot duplicate the arm and hand actions executed in the water, the swim bench does allow the swimmer to incorporate in one motion most of the muscle groups and the mechanics required during sprint swimming (Costill et al., 1980). The developments in dry-land ergometry that have followed the development of the swim bench have resulted in interesting investigations and meaningful research findings that have enhanced our understanding of swimming physiology. If the current limitations in the design of dry-land ergometry are addressed, it is certain that research involving the use of dry-land ergometry in swimming will progress further. Here, it should be emphasised that the aim of developing dry-land ergometry is, by no means, to replace water-based testing methods, but rather to offer a useful alternative for those assessments that are currently not possible to conduct in the water.

6.7. Conclusion

The findings of the component studies in this thesis demonstrated that dry-land ergometry may be a valuable laboratory-based tool in assessment of physiological responses to exercise in swimmers. It offers opportunities for research, such as the measurement of arm and leg power output and continuous measurement of cardiopulmonary and metabolic responses to arm-pulling, leg-kicking and combined arm-leg exercise (Chapters 3, 4 and 5). Such assessments were not possible previously when using other types of water-based ergometry. Also, it was shown in Chapter 5 that dry-land ergometry measurements compare well with water-based measurements. However, the use of dry-land ergometry presents several limitations. These limitations are mainly associated with the design of the arm-pulling, leg-kicking and combined arm-leg ergometers. Certainly, these limitations need to be addressed in the future to improve the design of this ergometry, thereby offering a more realistic approach in dry-land testing of swimmers. In overall, it was shown in the studies of this thesis that through the use of dry-land ergometry it is possible to investigate in the laboratory some aspects of swimming physiology that have not been possible previously.

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APPENDIX A

PHYSIOLOGY OF EXERCISE LABORATORIES
37 Landsowne Road, Bedford MK40 2BZ

DE MONTFORT UNIVERSITY BEDFORD

VO2 RESPONSES TO ARM AND LEG EXERCISE USING DRY-LAND ERGOMETRY FOR SWIMMERS.

INFORMED CONSENT FORM

Name: _____

Address _____ Telephone:_____

INFORMATION ABOUT THE TEST

The tests you are about to undertake will involve exercise on **a swim bench and a leg-kicking machine.**
The exercise will gradually increase in intensity from easy to fairly hard, until you feel that you cannot exercise any more.
Your **heart rate** will be constantly monitored, using a chest strap electrode.
Your **oxygen uptake** will be monitored, which means you will be breathing into a mouthpiece linked to direct gas analysis equipment.
Your *stature and body mass* will be measured before testing.

You will be free to stop the test at any time if you so desire.

THIS SECTION TO BE COMPLETED AT THE TIME OF THE TEST

I, _____ fully understand what is involved in taking part in this assessment and do so of my own free will. Any questions I have about the test session or my participation have been answered to my full satisfaction. All information I have given on the medical questionnaire overleaf is correct, and should be treated as confidential.

Signed: _____ Date: _____

Signature of investigator :_____

Physiology of Exercise Laboratories
37 Landsowne Road, Bedford MK40 2BZ

DE MONTFORT UNIVERSITY BEDFORD

PRE-TEST MEDICAL QUESTIONNAIRE

Name_____ Date of Birth _____ Age: _____ Sex: _____

1. How would you describe your present level of activity? (please circle as appropriate) — Sedentary/ Moderately active/ Active/ Highly active*
2. How would you describe your present level of fitness? — Unfit/ Moderately fit/ Trained/ Highly trained*
3. How would you consider your present body weight? — Underweight/ Ideal /Slightly over/ very overweight*
4. Smoking habits:
   - Currently non-smoker Yes/no*
   - A previous smoker Yes/no* ___ per day How long since stopping? ____ years
   - Occasional smoker Yes/no* ___ per day
   - Regular smoker Yes/no* ___ per day
5. Do you drink alcohol? Yes/no*
   If Yes, do you have: the occasional drink / a drink every day / more than one drink a day*
6. Have you had to consult your doctor within the last six months? Yes/ no* If yes, please give details to the tester.
7. Are you presently taking any form of medication? Yes/no* If yes, please give details to the tester.
8. Do you suffer, or have you ever suffered from:
   - Diabetes Yes/no* Asthma Yes/no*
   - Epilepsy Yes/no* Bronchitis Yes/no*
   - Any form of heart complaint? Yes/no*
   - Reynauds disease Yes/no*
   - Marfan syndrome Yes/no*
   - Aneurism or embolism? Yes/no*
9. Is there a history of heart disease in your family? Yes/no*
10. Do you currently have any form of muscle or joint injury? Yes/no*
11. Have you had any cause to suspend your normal training in the last two weeks? Yes/no*
12. Is there anything to your knowledge that may prevent you from successfully completing the tests that have been outlined to you? Yes/no*
13. Please read the following questions:
    - a Are you suffering from any known active, serious infection?
    - b Have you had jaundice within the previous year?
    - c Have you ever had any form of hepatitis ?
    - d Are you HIV antibody positive?
    - e Have you had unprotected sexual intercourse with any person from a HIV high risk population (egAfrica,Thailand, Miami)?
    - f Have you ever been involved in intravenous drug use?
    - g Are you haemophiliac?

    If you have anwered yes to any of questions a - g, please sign here: _____

    If you have anwered no to all of questions a - g, please sign here: _____

CODE OF PRACTICE FOR BLOOD SAMPLING (FINGER PRICK)

REFERENCES

De Montfort University (1995) *Health and Safety Policy: SP3/22/95 The Handling of Blood and Tissue Specimens.*

Hale, T., Armstrong, N., Hardman, A., Jakeman, P., Sharp, C. and Winter, E.M. (1988) *Position Statement on the Physiological Assessment of the Elite Competitor* (Second Edition). British Association of Sports Sciences, 6-4.

Only those who have received appropriate training are authorised to take finger prick blood samples.

1. Screen subjects using Appendix xiv pages 89–92 to ascertain if they are at risk of carrying AIDS or Hepatitis B. Exclude subjects in this category.

2. Exclude subjects who have obvious open wounds on the hands.

3. Any cuts on the experimenter's hands or wrists should be covered with a waterproof adhesive dressing before samples are taken.

4. Regularly laundered coats should be worn.

5. Prepare the tray with the :
   - ☐ Lancets or autolets
   - ☐ Sterile swabs (*Mediswabs* or similar specially prepared product)
   - ☐ Appropriately labelled and prepared sample tubes
   - ☐ Hazard bags
   - ☐ Sharp keeper
   - ☐ Bleach

6. The experimenter and the subject should wash their hands thoroughly with soap and water using a nail brush if necessary.

7. A "no touch" technique is employed and disposable gloves should be worn when samples are both taken and handled.

8. Swab the site of the puncture and put the swabs in the hazard bag.

9. Stab the clean area with a lancet or autolet and take the sample into the capillary tube.

10. Transfer the sample into the sample container and mix thoroughly.

11. Used lancets should be placed in a sharpkeeper container marked with the OSHA Biohazard symbol. The sharpkeeper should be sealed when the experiment has finished and be placed in a yellow clinical waste bag marked *Clinical Waste* for incineration. Discarded capillary tubes should be treated in the same manner. Used swabs and all non-sharp material should be placed in the clinical waste disposal bag.

12. Cover the puncture site with a waterproof adhesive dressing.

13. Any blood that has contaminated the experiment should be washed off with soap and water.

14. Any spillage of blood should be cleaned with a swab that contains bacteriocide, 2 % bleach.

15. Swab down the handlebars or support rail of the ergometer.

16. Wash hands before leaving the laboratory.

BLOOD SAMPLING CODE OF PRACTICE (VENEPUNCTURE)

REFERENCES

De Montfort University (1995) *Health and Safety Policy: SP3/22/95 The Handling of Blood and Tissue Specimens.*

Hale, T., Armstrong, N., Hardman, A., Jakeman, P., Sharp, C. and Winter E.M. (1988) *The Physiological Assessment of the Elite Competitor* (Second Edition). British Association of Sports Sciences, 6-4.

Only those who have received appropriate training and a certificate of competence are authorised to take venepuncture blood samples.

1. Screen subjects using Appendix xiv pages 89–92 to ascertain if they are at risk of carrying AIDS or Hepatitis B. Exclude subjects in this category.

2. Any cuts on the experimenter's hands or wrists should be covered with a waterproof adhesive dressing before samples are taken.

3. Regularly laundered coats should be worn.

4. Prepare the tray with the :
   - ☐ Syringes and needles
   - ☐ Sterile swabs (Mediswabs or similar specially prepared product) or cotton wool swabs impregnated with 70% alcohol.
   - ☐ Appropriately labelled and prepared sample tubes
   - ☐ Plaster-of-Paris Syringe/Needle Holder
   - ☐ Tourniquet
   - ☐ Yellow Clinical Waste disposal bags
   - ☐ Sharps keeper
   - ☐ Bleach or disinfectant spray

5. The experimenter should wash his or her hands thoroughly with bactericidal soap and water using a nail brush if necessary.

6. Assemble the syringe and needle, check it is functioning properly and leave ready for use with needle in its plastic cover placed in the Holder.

7. Disposable gloves should be worn when samples are both taken and handled.

8. Place the tourniquet around the subject's upper arm, above the elbow, and tell him or her to clench their fist repeatedly.

9. Select a vein and swab the site of the puncture. Put used swabs in the Clinical Waste Disposal bag.

10. Introduce the hypodermic needle to the vein and draw the sample into the syringe.

11. Release tourniquet and fist, cover puncture site with swab and withdraw needle. Tell the subject to press down on swab firmly to stop bleeding.

12. Return the syringe+needle to the Holder and carefully remove the syringe.
NEVER HOLD THE NEEDLE COVER IN YOUR HAND WHEN REPLACING NEEDLE.

13. Transfer the sample into the sample container and mix thoroughly. (Do not shake).

14. Used syringes and needles should be placed in a sharpskeeper BS no 7320, marked with the OSHA Biohazard symbol. The sharpskeeper should be closed when the experiment has finished. Used swabs and all non-sharps material should be placed in the clinical waste disposal bag, which should be similarly marked.

    When 75% full, the sharpskeeper should be sealed and sent for disposal by incineration, according to the University's Code of Practice for Collection, Storage and Disposal of Clinical Waste. Waste bags, when 75% full, should be sealed and stored in the designated storage bin to await disposal in the same way.

15. When bleeding has stopped, swab the puncture site and cover with a dressing.

16. Any spillage of blood should be cleaned with a swab that contains bacteriocide, e.g. 2% bleach or disinfectant spray.

17. Wash hands before leaving the laboratory.

See also:

Code of Practice for Collection, Storage and Disposal of Clinical Waste
Disinfectant and Spillage Policy

COLLECTION, STORAGE AND DISPOSAL OF CLINICAL WASTE CODE OF PRACTICE

REFERENCE

De Montfort University (1995). *Health and Safety Policy SP/63/95: Safe Disposal of Clinical Waste.*

1. Clinical waste Category groups A and B, is generated by collection of samples and clearing up residues of blood and other fluids (urine, saliva, sweat) from humans, in the Physiology of Exercise Laboratories.

2. The designated storage area is in the Prep room, Physiology of Exercise Laboratories, Lansdowne, Bedford.

3. All authorised persons should be trained in the handling and collection of Clinical Waste and named on the Risk Assessment Reference Number DMUB/PHYS/25

4. Hepatitis & Tetanus Vaccinations should be considered for all persons handling Clinical Waste.

5. Consult:
   - Risk Assessment DMUB/PHYS/25 Collection Storage and Disposal of Clinical Waste.
   - Risk Assessment DMUB/PHYS/09 Blood Collection.
   - Codes of Practice for Sampling Blood and other body fluids.
   - Disinfectant and Spills Policy.

6. Preparation:
   - ☐ Wear correct protective clothing *i.e.* latex gloves and white coat.
   - ☐ Wear goggles if there is a need for eye protection.
   - ☐ Check the supply of gloves. Gloves must be changed if they become contaminated or torn.
   - ☐ Check that there is sufficient room in sharps boxes and bags. Have spares available.
   - ☐ Check that there are sufficient cotton wool swabs and tissues for use as swabs.
   - ☐ Check that there is a spillage kit and you know how to use it.
   - ☐ Check that there is sufficient time allocated for task.
   - ☐ Check that you will not be distracted from the procedure by interruption or other duties. Put a sign on the door indication that sampling is in progress.

7. **Collection Trolley:**

Marked *Designated area - for use with Human Blood.*

The Trolley should hold the following:

- ❑ A flip-top bin which contains a yellow clinical waste bag (40 x 36 cm) marked *For incineration only* and *Physiology Dept.* To be used for contaminated swabs, gloves, tissues etc. **NO SHARPS.**
- ❑ A Sharps container, 7 litre size - to be used for syringe needles, capillary tubes, lancets and anything which might pierce the plastic bags.
- ❑ A Spill Kit containing freshly prepared 2% hypochlorite solution, or a sanitising spray such as Klercide5 (contains Cryocide), produced by Shield Medicare Ltd, 5 Hurlands Business Park, Hurlands Close, Farnham, Surrey GU9 9JE . See also Disinfectant and Spills Policy.

The Trolley and all equipment must be kept clean and tidy at all times and disinfected after each session using solutions from Spill Kit.

All used cleaning materials must be deposited in the Clinical waste bag.

When not in use Trolley must be returned to the Physiology Prep. room

Hands should be washed thoroughly using bactericidal soap after dealing with clinical waste.

8. **Storage**

- ❑ When 75% full, the Small Yellow bags should be removed from the flip-top bin on the Trolley and sealed. They should then be placed in the 65 litre yellow plastic bin which is also in the Prep room.
- ❑ When 75% full, the Sharps container should be removed from Trolley and sealed. It should then be stored next to the yellow plastic bin in the Prep room.

The Prep room door should be kept locked when the room is not in use.

9. **Disposal**

- ❑ The yellow plastic bin and Sharps containers will be collected by PHS (Tel: 01455 843375 or 0585 254583) as arranged by the Health and Safety Office
- ❑ Waste will be collected from the Prep room, Physiology labs. by PHS staff.
- ❑ A replacement 65 litre yellow plastic bin and Sharps containers will be left at the same time.

10. **Accidents**

First aid: Swab contaminated skin with-70% alcohol (in bottle on trolley)

Any accidents , incidents or near misses must be reported to Physiology Technicians (Caroline Reavell or Sue Clark) and Area Safety Manager (Warwick Riley). They will then forward information to the Health and Safety Office.

APPENDIX B

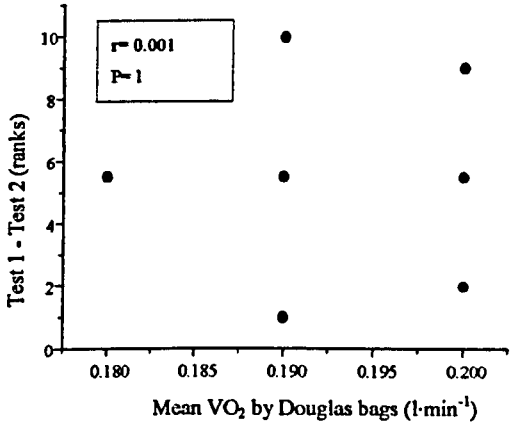


Figure 1. A plot of the absolute differences against their individual means to show the relationship between the measurement error and the magnitude of the measured variable for resting $\dot{V}O_2$ values measured by the Douglas bags gas analysis method.

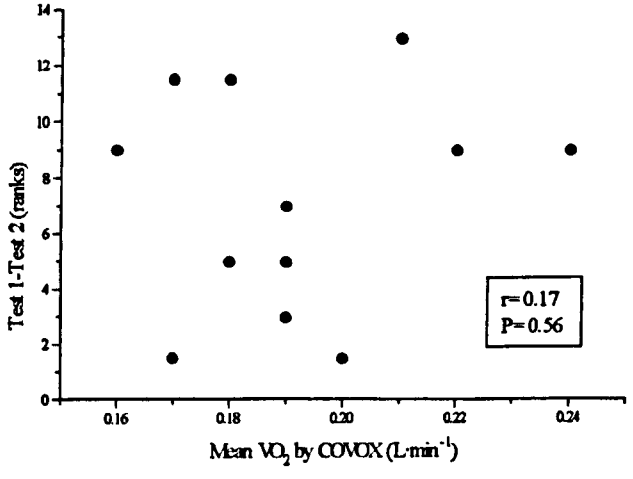


Figure 2. A plot of the absolute differences against their individual means to show the relationship between the measurement error and the magnitude of the measured variable resting $\dot{V}O_2$ values measured by the Douglas bags gas analysis method. The r-value denotes slight heteroscedasticity.

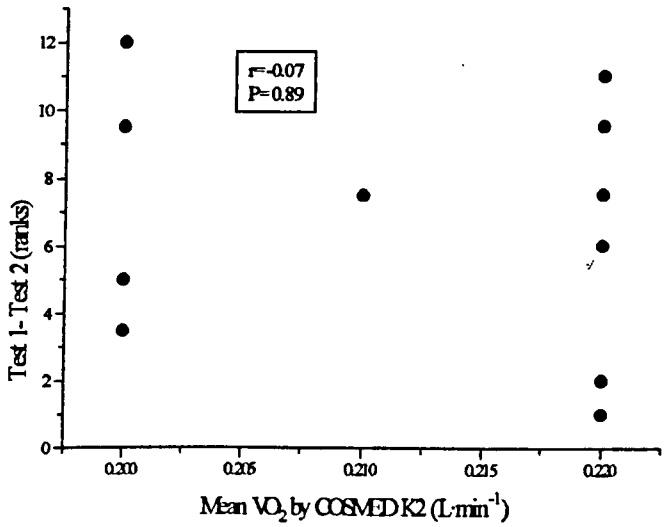


Figure 3. A plot of the absolute differences against their individual means to show the relationship between the measurement error and the magnitude of the measured variable for resting $\dot{V}O_2$ values measured by the COSMED K2 gas analysis method.

APPENDIX C

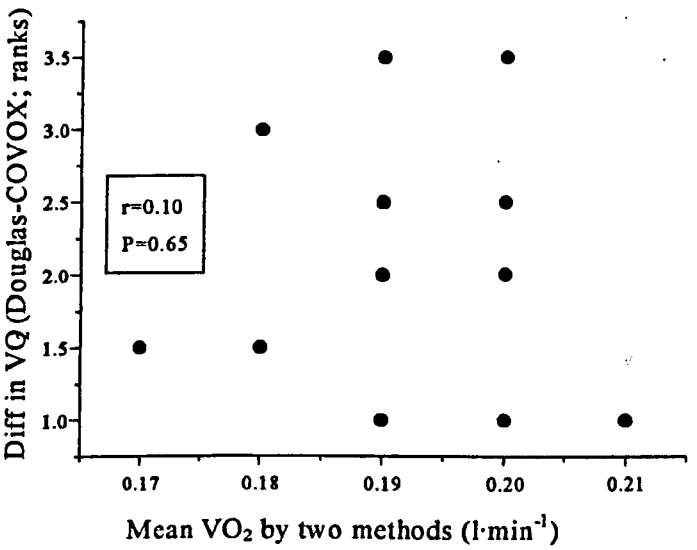


Figure 1. A plot of the absolute differences against their individual means showing the relationship between the measurement error and the magnitude of the measured variable in resting oxygen uptake ($\dot{V}O_2$; ranks) between two methods (Douglas bags-COVOX Microlab) and their individual means ($\dot{V}O_2$; l·min^{-1}).

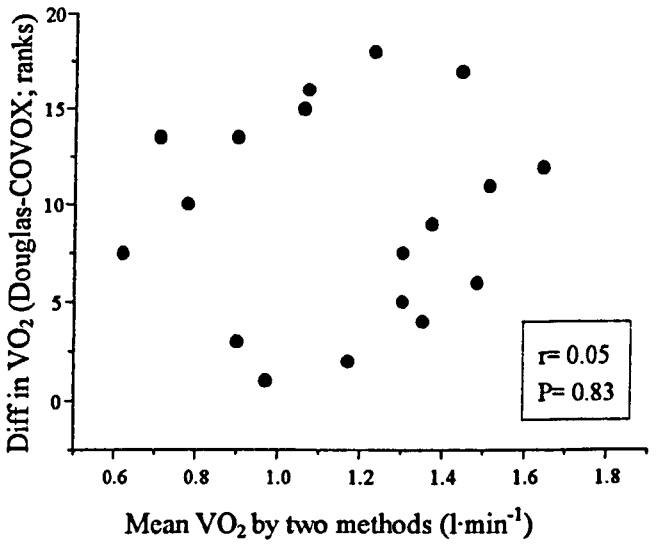


Figure 2. A plot of the absolute differences in submaximal oxygen uptake ($\dot{V}O_2$; ranks) between two methods of gas analysis (Douglas bags–COVOX Microlab) and their individual means ($\dot{V}O_2$; l·min^{-1}) for examination of the measurement error.

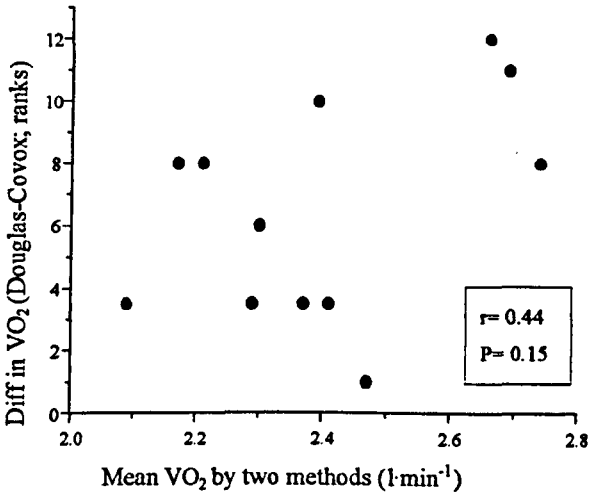


Figure 3. A plot of the absolute differences in maximal oxygen uptake ($\dot{V}O_2$; ranks) between two methods of gas analysis (Douglas bags–COVOX Microlab) and their individual means ($\dot{V}O_2$; $l \cdot min^{-1}$) for examination of the measurement error.

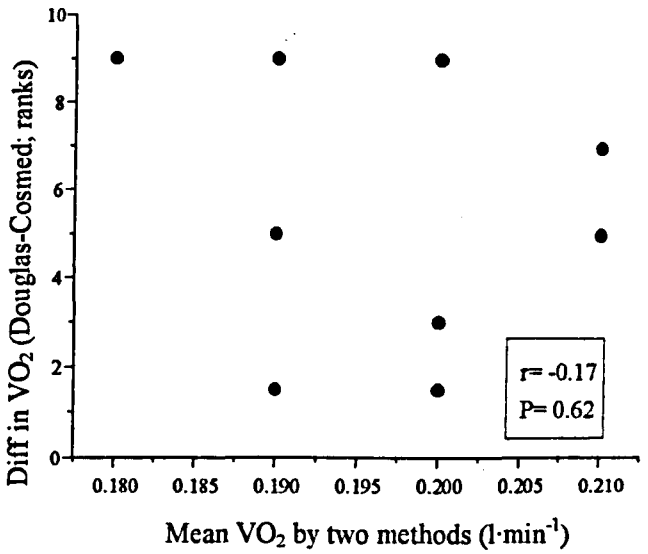


Figure 4. A plot of the absolute differences in resting oxygen uptake ($\dot{V}O_2$; ranks) between two methods of gas analysis (Douglas bags–COSMED K2) and their individual means ($\dot{V}O_2$; $l \cdot min^{-1}$) for examination of the measurement error.

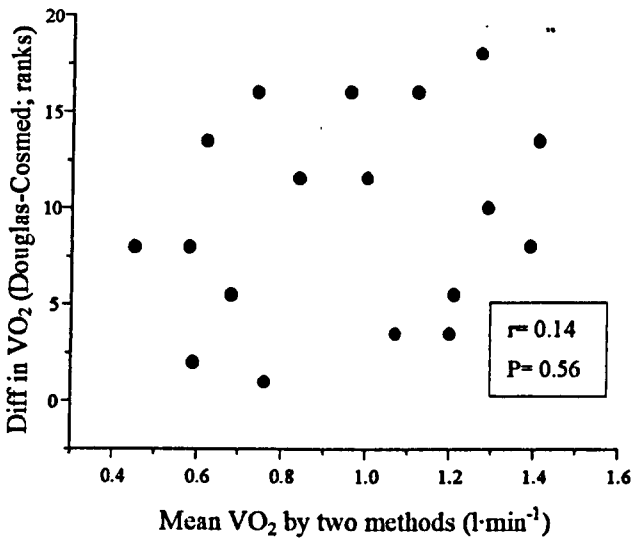


Figure 5. A plot of the absolute differences in submaximal oxygen uptake ($\dot{V}O_2$; ranks) between two methods of gas analysis (Douglas bags–COSMED K2) and their individual means ($\dot{V}O_2$; $l \cdot min^{-1}$) for examination of the measurement error.

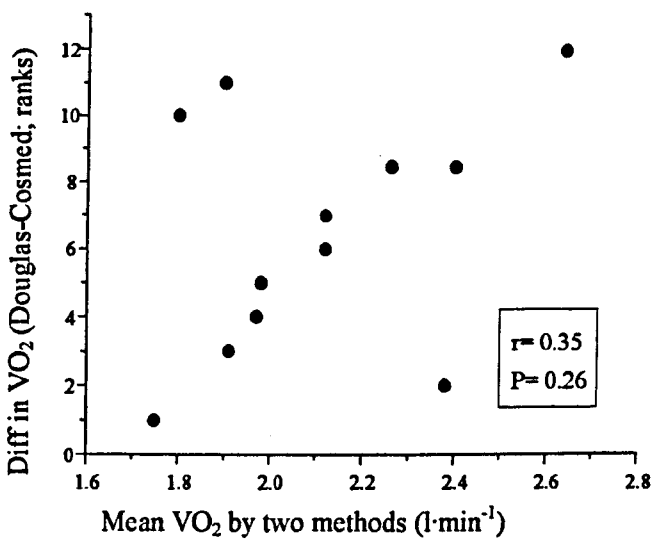


Figure 6. A plot of the absolute differences in maximal oxygen uptake ($\dot{V}O_2$; ranks) between two methods of gas analysis (Douglas bags–COSMED K2) and their individual means ($\dot{V}O_2$; $l \cdot min^{-1}$) for examination of the measurement error.

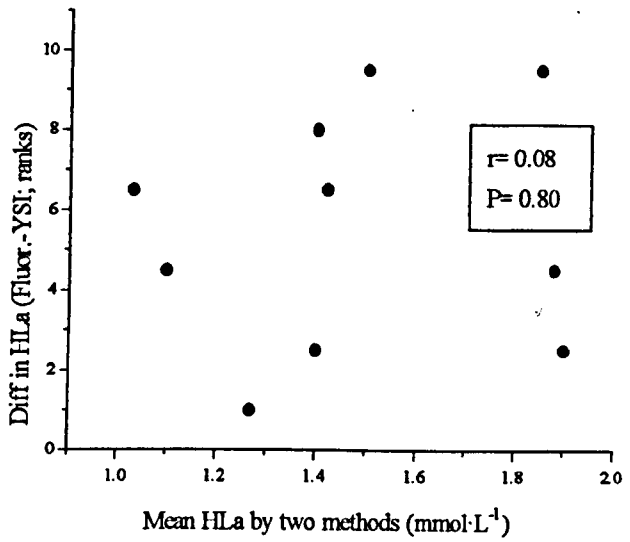


Figure 7. A plot of the absolute differences in low concentration of lactate (HLa; ranks) between two methods of blood lactate analysis (Fluorimeter–YSI) and their individual means (HLa; $mmol \cdot l^{-1}$) for examination of the measurement error.

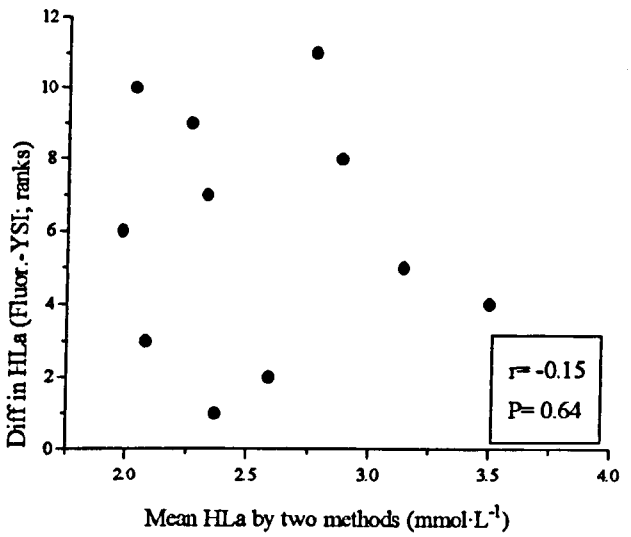


Figure 8. A plot of the absolute differences in medium concentration of lactate (HLa; ranks) between two methods of blood lactate analysis (Fluorimeter–YSI) and their individual means (HLa; $mmol \cdot l^{-1}$) for examination of the measurement error.

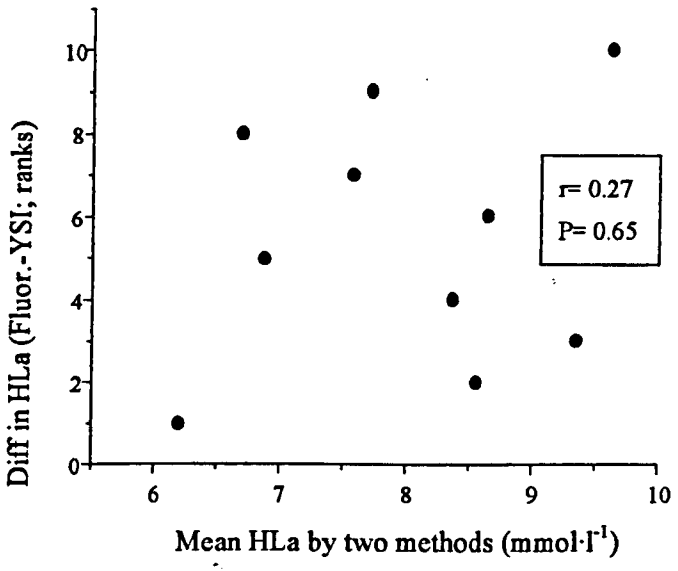
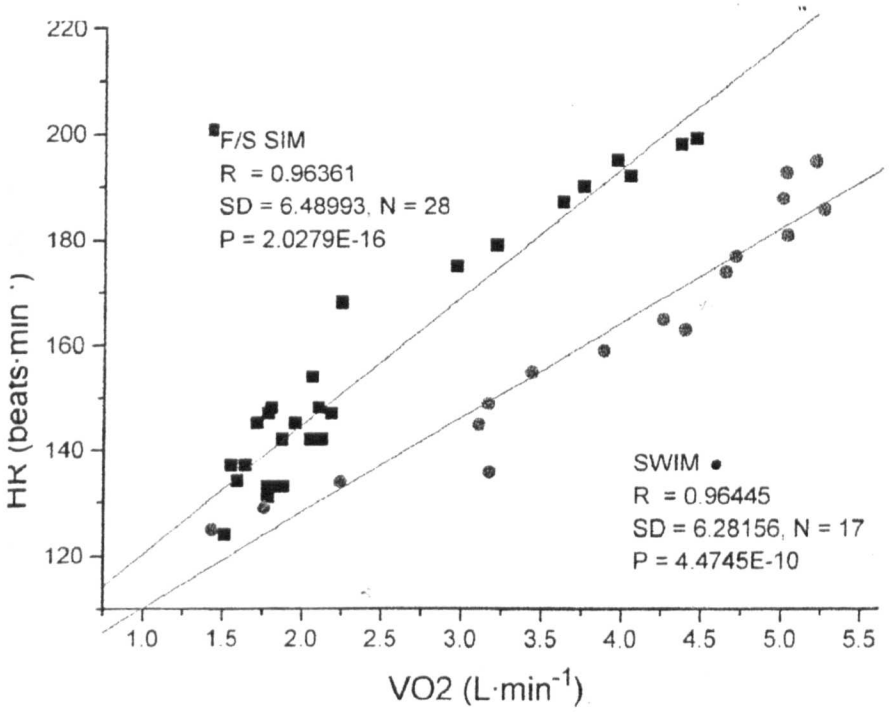
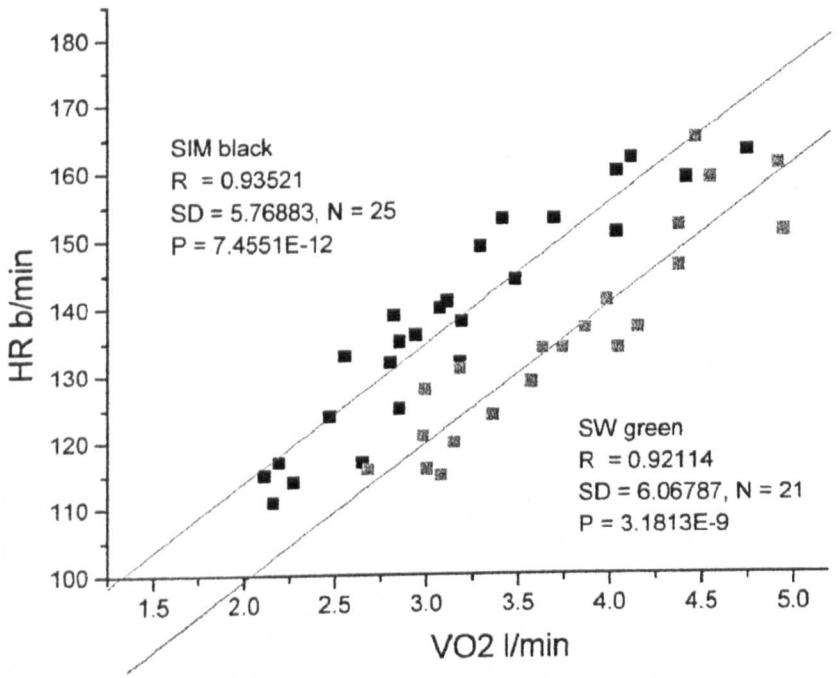
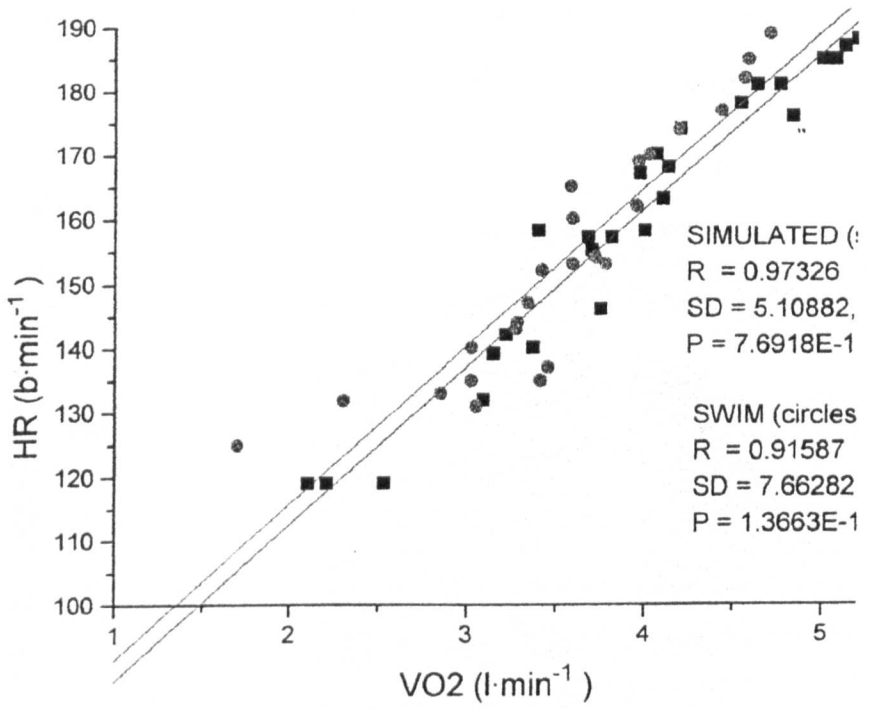


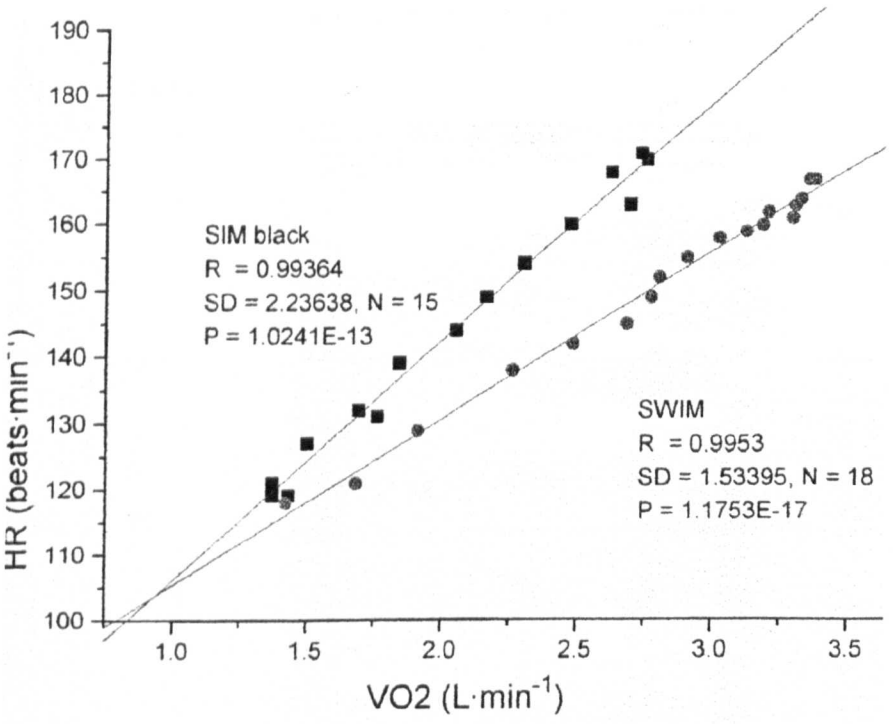
Figure 9. A plot of the absolute differences in high concentration of lactate (HLa; ranks) between two methods of blood lactate analysis (Fluorimeter–YSI) and their individual means (HLa; mmol·l^{-1}) for examination of the measurement error.

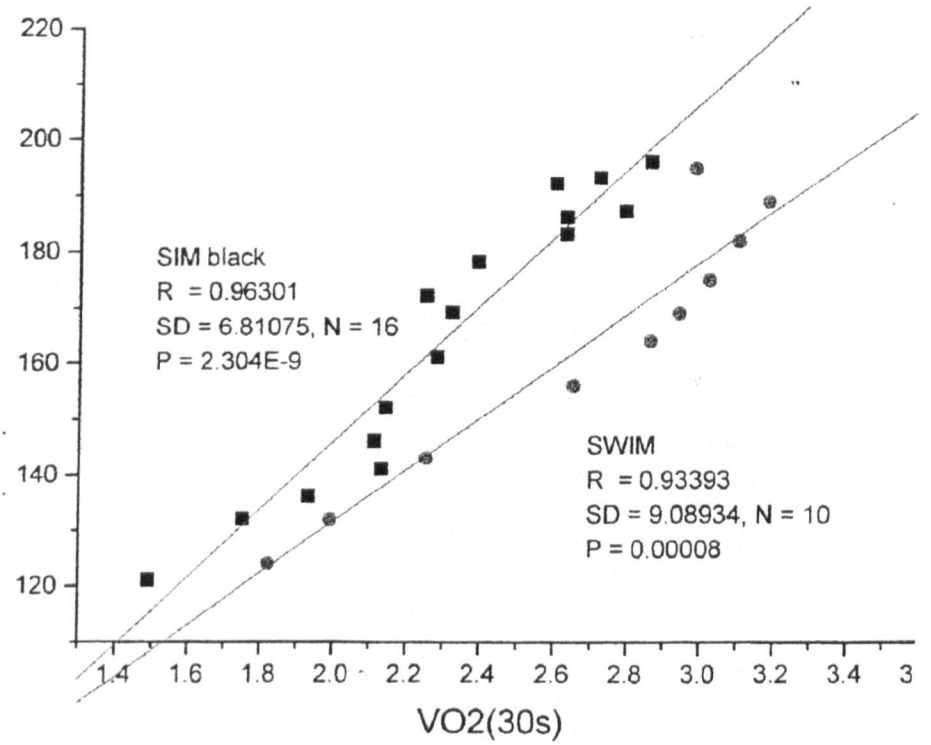
APPENDIX D

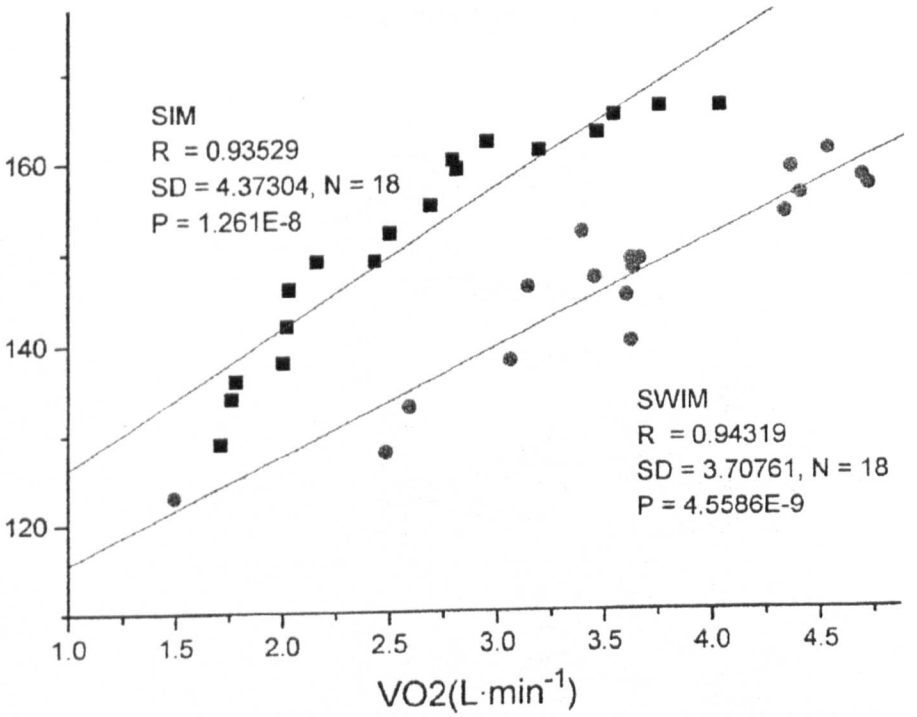

F/S SIM
R = 0.96361
SD = 6.48993, N = 28
P = 2.0279E-16
SWIM
R = 0.96445
SD = 6.28156, N = 17
P = 4.4745E-10
HR (beats·min⁻¹)
VO2 (L·min⁻¹)

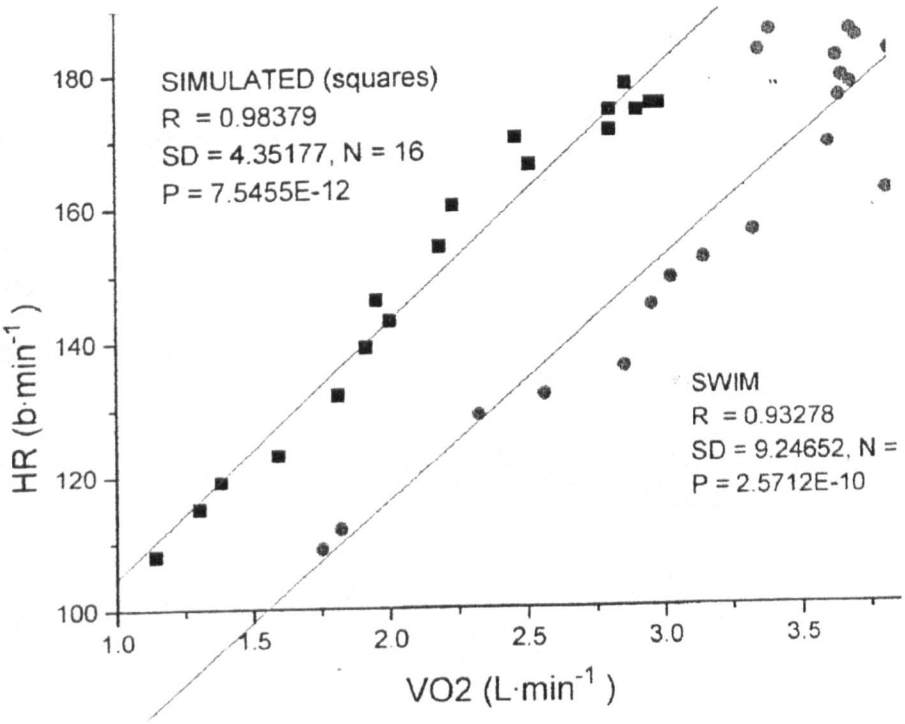

SIM black
R = 0.93521
SD = 5.76883, N = 25
P = 7.4551E-12
SW green
R = 0.92114
SD = 6.06787, N = 21
P = 3.1813E-9
HR b/min
VO2 l/min

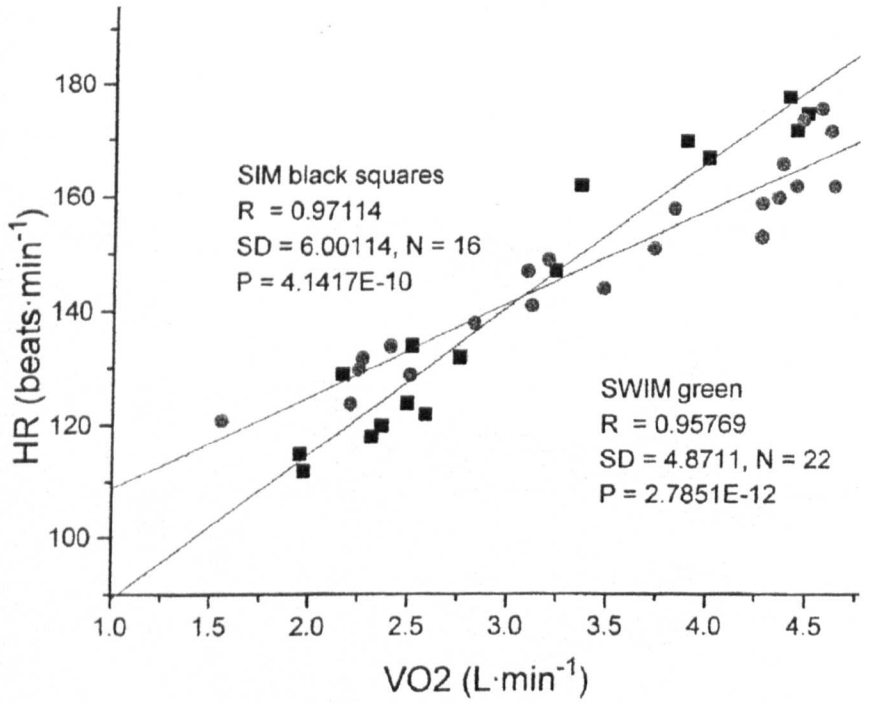

HR (b·min-1)
VO2 (l·min-1)
SIMULATED (
R = 0.97326
SD = 5.10882,
P = 7.6918E-1
SWIM (circles
R = 0.91587
SD = 7.66282
P = 1.3663E-1

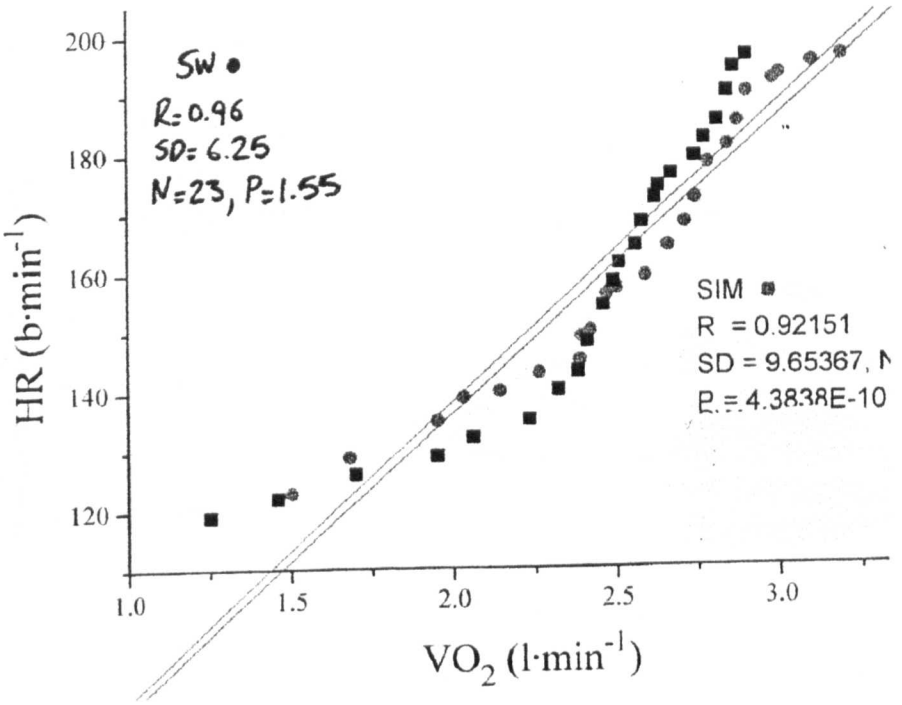

HR (beats·min-1)
VO2 (L·min-1)
SIM black
R = 0.99364
SD = 2.23638, N = 15
P = 1.0241E-13
SWIM
R = 0.9953
SD = 1.53395, N = 18
P = 1.1753E-17


SIM black
R = 0.96301
SD = 6.81075, N = 16
P = 2.304E-9
SWIM
R = 0.93393
SD = 9.08934, N = 10
P = 0.00008
VO2(30s)


SIM
R = 0.93529
SD = 4.37304, N = 18
P = 1.261E-8
SWIM
R = 0.94319
SD = 3.70761, N = 18
P = 4.5586E-9
VO2(L·min-1)


SIMULATED (squares)
R = 0.98379
SD = 4.35177, N = 16
P = 7.5455E-12
SWIM
R = 0.93278
SD = 9.24652, N =
P = 2.5712E-10
HR (b·min-1)
VO2 (L·min-1)
180
160
140
120
100
1.0
1.5
2.0
2.5
3.0
3.5


SIM black squares
R = 0.97114
SD = 6.00114, N = 16
P = 4.1417E-10
SWIM green
R = 0.95769
SD = 4.8711, N = 22
P = 2.7851E-12
HR (beats·min-1)
VO2 (L·min-1)
180
160
140
120
100
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5


SW
R=0.96
SD=6.25
N=23, P=1.55
SIM
R = 0.92151
SD = 9.65367, N
P = 4.3838E-10
HR (b·min-1)
VO2 (l·min-1)
200
180
160
140
120
1.0
1.5
2.0
2.5
3.0

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